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Mechanically defibrated wood in pulverized fuel firing

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo, August 12, 2013

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Abstract of master's thesis

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Abstract:

By replacing coal with renewable fuels, such as wood, the consumption of coal and the amount of fossil fuel emissions can be reduced. The wood fuels need however processing before combustion in pulverized fuel firing boilers. The aim of this work is to study the applicability of the DustComb-process as a pretreatment method for wood fuels.

The principle of the DustComb-process is to defibrate the woody feedstock with a mechanical defibrator, and the produced fines are dried with a flash dryer integrated into the process. The dried fines are either fed into a pulverized fuel burner or stored for later use. In this work, the co-firing of biomass in a pulverized coal boiler is discussed, and the principles of mechanical defibration and flash drying are explained. In the experimental part of this study, the influence of the disc clearance on the defibrator's specific energy consumption is determined. The disc clearance in the defibration tests are varied between 0.60 and 1.80 mm. Also the effect of the particle size on the drying rate is studied. In the calculations part, the costs of producing the DustComb-fuel are estimated and their dependence on the market price of electricity, the price of heat, and the price of the feedstock are evaluated. The costs are further compared with the market prices of coal and wood pellets.

The experimental results show that the energy consumption of the defibration starts to increase rapidly when the disc clearance is narrowed from 1.00 mm. According to the test results, the studied particle size changes do not have any remarkable effect on the drying rate of the material. A significant observation is that a great amount of the water in the wood is evaporated already during the defibration (16–25% of the initial moisture). The calculation results show that the production of the DustComb-fuel is economically viable when compared to the price of coal, and especially when compared to the price of wood pellets. The results also show that the costs of the energy needed for the DustComb-process are low compared to the price of the raw material.

Keywords: DustComb, biomass, pulverized fuel firing, co-firing, mechanical pulping, flash drying, wood fuel

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Abstract of master's thesis

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Tiivistelmä:

Kivihiilen käyttöä ja siitä muodostuvien päästöjen määrää voidaan vähentää korvaamalla kivihiili uusiutuvilla polttoaineilla, kuten esimerkiksi puulla. Puupolttoaine vaatii kuitenkin esikäsittelyä ennen polttamista pölypolttokattilassa. Tämän työn tarkoitus on tutkia DustComb-prosessin soveltuvuutta puupolttoaineen esikäsittelymenetelmänä.

DustComb-prosessin ideana on kuiduttaa puuperäinen raaka-aine mekaanisella kuiduttimella, jonka jälkeen tuotettu aines kuivataan prosessiin integroidulla flash-kuivaimella. Valmis polttoaine syötetään joko suoraan pölypolttimeen tai varastoidaan myöhempää käyttöä varten. Tässä työssä on aiemman kirjallisuuden perusteella selostettu biomassan seospoltto hiilipölykattilassa sekä mekaanisen kuidutuksen ja flash-kuivauksen perusteet. Työn kokeellisessa osiossa on tutkittu miten kuiduttimen teräväli vaikuttaa kuidutuksen ominaisenergiankulutukseen ja miten merkittävästi materiaalin partikkelikoko vaikuttaa sen kuivumisnopeuteen. Kuidutuskokeissa teräväliä vaihdeltiin 0.60 ja 1.80 mm:n välillä. Lisäksi on laskettu DustComb-polttoaineen valmistuskustannuksia ja niiden riippuvuutta mm. sähkön markkinahinnasta, lämmön hinnasta sekä raaka-aineen hinnasta. Tuloksia on verrattu kivihiilen ja puupellettien markkinahintaan.

Kokeelliset tulokset osoittavat että 1.00 mm terävälin kohdalla energiankulutus alkaa nousta selvästi, kun väliä pienennetään. Työssä tutkittujen partikkelikokojen vaihtelu ei tulosten perusteella vaikuta merkittävästi materiaalin kuivumisnopeuteen. Merkittävä havainto on, että suuri osa puun sisältämästä kosteudesta poistuu jo kuidutuksen aikana (16–25% puun alkukosteudesta). Laskennallisen osion tuloksista selviää että DustComb-polttoainetta on mahdollista valmistaa kilpailukykyisillä kustannuksilla kivihiilen, sekä erityisesti puupellettien markkinahintaan verrattuna. Lisäksi selviää että DustComb-menetelmää varten tarvittavan energian kustannukset ovat pienet siinä käytetyn raaka-aineen hintaan verrattuna.

Avainsanat: DustComb, biomassa, pölypoltto, seospoltto, mekaaninen kuidutus, flash-kuivaus, puupolttoaine

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Espoo, August 12, 2013

Henri Lohilahti

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Symbols and abbreviations

Symbols

$C_{CHP\text{-}heat}$	[€/MWh]	Price of heat
C_{el}	[€/MWh]	Market price of electricity
C_{Fuel}	[€/MWh]	Price of the fuel
$C_{Fuel,\ CHP\text{-}heat}$	[€/MWh]	Fuel costs for the produced heat in a CHP-plant
$C_{Fuel,\ comb}$	[€/MWh]	Total fuel costs for the combined production
$C_{Fuel,\ el}$	[€/MWh]	Fuel costs for the produced electricity
$C_{Fuel,\ heat}$	[€/MWh]	Fuel costs for the produced heat
M_{db}		Moisture content on dry basis
M_{wb}		Moisture content on wet basis
P_{idle}	[W]	Idling power
Q_{GHV}	[MJ/kg]	Gross heating value
Q_{HHV}	[MJ/kg]	Higher heating value
Q_{resid}	[%]	Residual energy
T	[°C]	Temperature
X_H	[%]	Concentration of hydrogen
a		Amount of pulses sent to the defibrator
l_w	[MJ/kg]	Heat of evaporation
m_{dm}	[kg]	Mass of dry matter
m_{dry}	[kg]	Dry mass
m_w	[kg]	Mass of water
t	[s]	Duration
Δt	[s]	Time period
α		Power to heat ratio
η		Plant efficiency

Abbreviations

CFB	Circulating fluidized bed
CHP	Combined heat and power, cogeneration
EU	European Union
EU-27	All 27 member states of the European Union in 1.1.2013
FBD	Fluidized bed dryer
GHV	Gross heating value
HHV	Higher heating value
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
MC	Moisture content
Mtoe	Million tonnes of oil equivalent

RMP	Refiner mechanical pulp
SEC	Specific energy consumption
TFC	Total final consumption
TPES	Total primary energy supply
VOC	Volatile organic compound
d.b	Dry basis
rpm	Revolutions per minute
w.b	Wet basis

Elements

Al	Aluminium
Ca	Calcium
Cl	Chlorine
Fe	Iron
K	Potassium
Mg	Magnesium
N	Nitrogen
Na	Sodium
S	Sulfur
Si	Silicon

Compounds

CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
H_2	Molecular hydrogen
H_2O	Water
H_2S	Hydrogen sulfide
KCl	Potassium chloride
NaCl	Sodium chloride
NH_3	Ammonia
NO_x	Nitrogen oxides
SO_x	Sulfur oxides

1 Introduction

The energy demand is increasing worldwide and the share of fossil fuels in the utilized energy sources is dominant. According to the statistics published by the International Energy Agency (IEA) [1], 81% of the total primary energy supply in the world in 2010 originated from fossil sources (including peat). The combustion of fossil fuels releases carbon stored in the ground and increases the carbon dioxide (CO_2) content in the atmosphere. CO_2 is estimated as the most important greenhouse gas. Greenhouse gases are assumed to have a great influence on the global warming. The Intergovernmental Panel on Climate Change (IPCC) has reported that the emissions from continued use of fossil fuels will lead to a temperature increase from 1.4°C up to 5.8°C over the period from 1990 to 2100. [1] [2] [3]

Like all fossil fuels, also the coal reserves are limited and the coal price is sensitive to fluctuations. Coal is a common fuel in power plants: 40.6% of the electricity in the world was generated from coal and peat in 2010. [1] Thus, there is a great potential in replacing the coal with renewable and carbon neutral biomass. Wood and coal have similar properties, and wood suits well to be combusted together with coal in existing plants. If the biofuel can be burned with same equipment as coal, no great investments are needed. The capability to burn several different fuels also brings more reliability to the economy of the plant. [1] [4]

When dead biomass decomposes in the nature, harmful emissions, such as methane, are released. So, besides the need for reducing the usage of fossil fuels, also significant amounts of harmful emissions can be avoided by recovering forest residues. However, the technical limitations of using biomass as a fuel are the low heating value and low bulk density. These factors have an increasing effect on the transportation needs. Also the high moisture content in biomass brings challenges, mainly for the combustion quality and efficiency. [3] [4] [5]

Biomass belongs to the renewable energy sources, consisting of all organic material originated from plants, such as trees, crops, algae, animal materials and organic waste. The main types of biomass can be defined as woody plants (e.g. bark and forest residues), herbaceous plants/grasses, aquatic plants, and manures. This work will though focus on the woody biomass. [2] [3]

Due to varying fuel requirements in different boiler types, grate fired or fluidized bed boilers are usually used for firing biomass, while coal is normally burned in pulverized fuel boilers. [6] One method to produce a wood fuel, which can be burned in pulverized coal boilers, is to defibrate the wood mechanically. The produced fines are dried with an integrated flash dryer before combustion. No previous reports are found about this method for such purpose. In this work, the integrated defibration and drying will be investigated, and the method will be called the DustComb-process.

The aim of this work is to evaluate the feasibility of the DustComb, when it is used to produce wood fines suitable for pulverized fuel firing. The experimental part in this work consists of two sections: the experimental tests and the calculations. In the first section, the specific energy consumptions of the defibration of wood to different fineness are calculated and compared. The operating costs of the DustComb-process are evaluated in the second section. The total production costs of the DustComb-fuel are calculated and compared with competing fuel prices. Possible carbon dioxide savings are also estimated in the second section.

The research questions to be answered in this work are:

- What is the optimal disc clearance in the defibrator for the DustComb-process?
- How much energy is required for the defibration?
- How much does different particle size of the fines affect the drying rate?
- What are the costs of producing the fuel with the DustComb-method?
- How profitable is the DustComb-fuel compared to coal?

Helsingin Energia has examined co-firing of wood pellets with coal. They have decided to start using wood pellets as a co-firing fuel in their coal-fired CHP-plants in 2015. A pellet share of 5-10% of the total fuel power is planned to be burned. They have estimated a yearly pellet demand of 100 000 tons, which is about one third of the current total pellet production in Finland and over half of the current amount of pellets consumed in Finland. [7]

The annual capacity of wood pellet production in Finland is calculated to be 700 000 tons. The yearly use of pellets in Finland is however estimated to increase to 850 000 tons by the year 2020. To meet the future needs, Finland has to either increase the production of wood pellets or increase the import of pellets. The limited capacity has a direct effect on the price of pellets. [7] Thus, the DustComb-method might be an alternative method to produce wood fuel suitable for co-firing in coal power plants. In this work, the DustComb-fuel is investigated and compared with wood pellets and coal.

2 Biomass as an energy source

All biomass, including wood and forest residues, are carbon neutral energy sources, which means that the same amount carbon is bound to new biomass during growth, as released when the biomass is burned. Due to the low sulfur and heavy metal contents in wood, it is a less polluting fuel than coal or crude oil. In addition, raw wood is usually less expensive than crude oil or natural gas. [2] [5]

Biomass is produced through photosynthesis by green plants. The energy from sunlight is transformed into chemical energy and stored in the plant as carbohydrates. During combustion, digestion or decomposition, the chemical bonds between carbon, hydrogen and oxygen molecules are broken and the stored energy is released. By pretreatment methods, the usability of biomass as a fuel can be increased. Fuels in gaseous, liquid and solid form can be produced by processing biomass. [2] [3] [8] This work concentrates though only on solid wood fuels.

In this chapter, the current worldwide use of biomass as a solid fuel is presented and the composition of woody biomass is discussed. Some biomass pretreatment methods to increase the usability of biomass as a fuel are also presented.

2.1 The use of biomass

The fossil fuels, such as coal and crude oil, have been the dominant energy sources since the industrialization. The usage of these resources has increased with the increasing energy demand. Recently, with growing environmental consciousness, awareness of global warming, and awareness of exhausting fossil resources, the significance of renewable energy sources has increased. For example, European Union (EU) has set as target for year 2020 a renewables share of 20% of total final energy consumption. During the last ten years, the share among all 27 EU's member states (EU-27) has increased from 8% to over 12%, which is presented in Figure 1. [9]

The proportion of renewables in the primary energy production in EU is 21%, amounting about 162 Mtoe (Figure 2 and Figure 3). The share of biomass and renewable wastes covers the majority of the produced primary energy from renewables. The amount of energy produced from biomass and renewable wastes in EU has increased to almost the double since year 2000, which can be seen in Figure 3. [9]

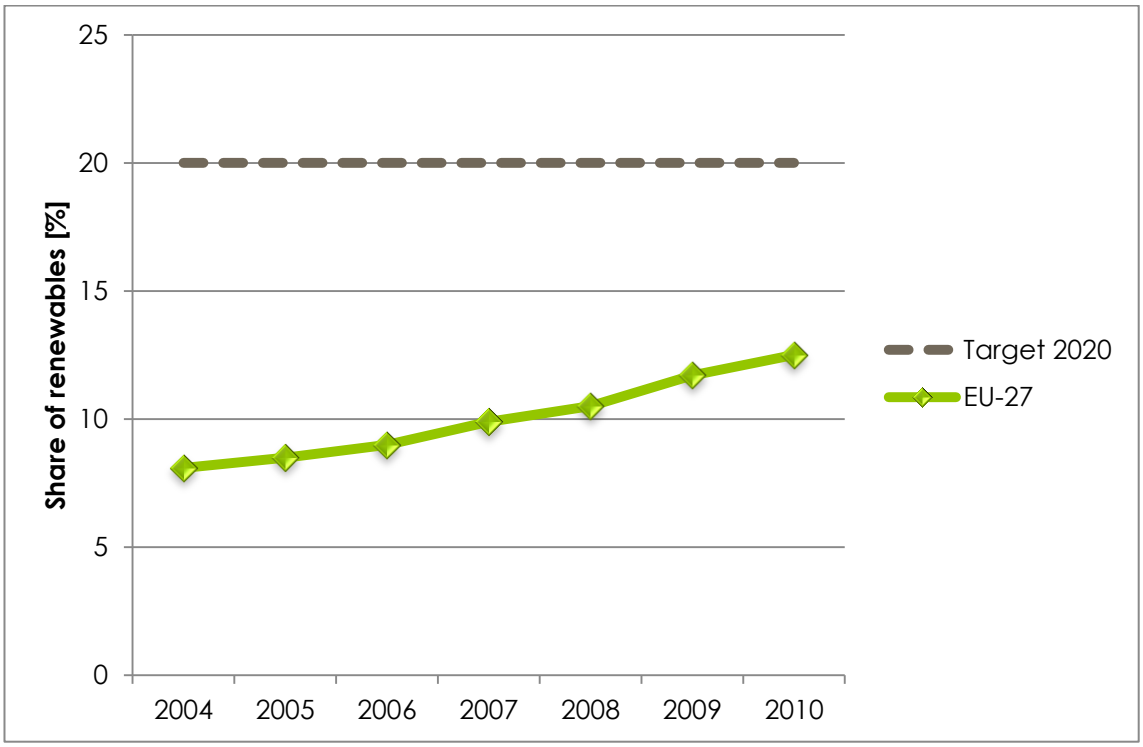

Figure 1. Share of renewable energy in gross final energy consumption, EU-27-countries. [9]

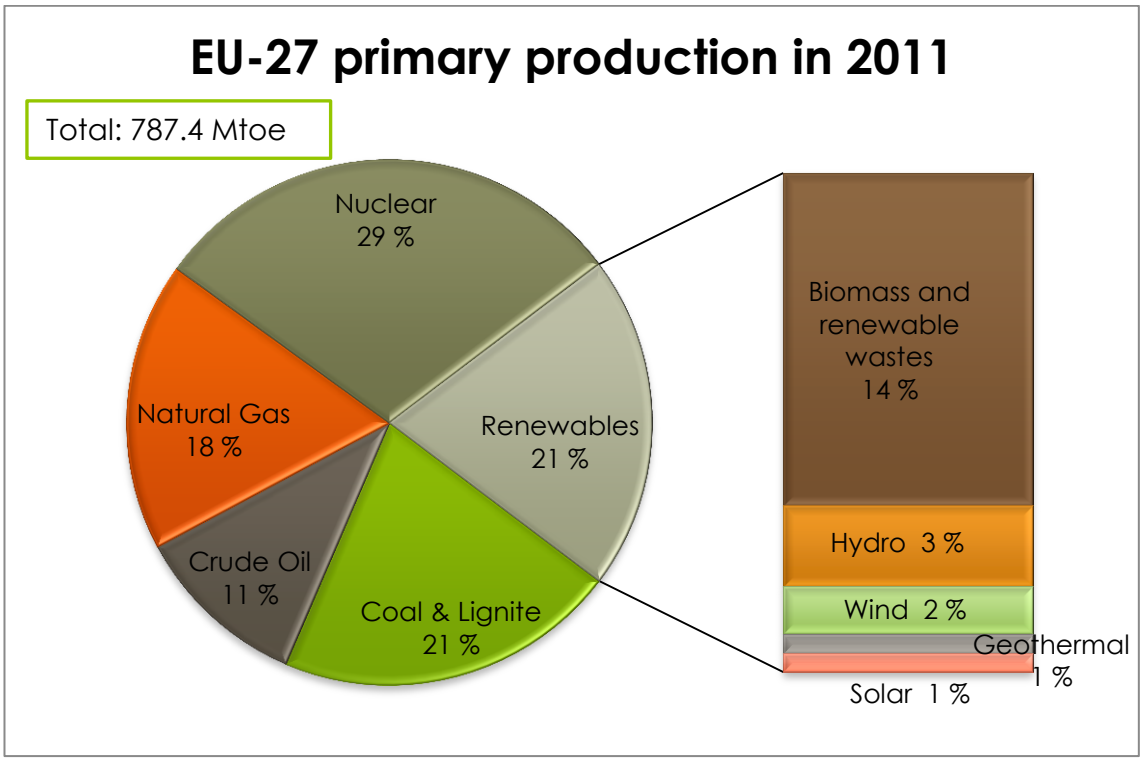

Figure 2. The fuel sources for primary energy production in the EU-27-countries. [9]

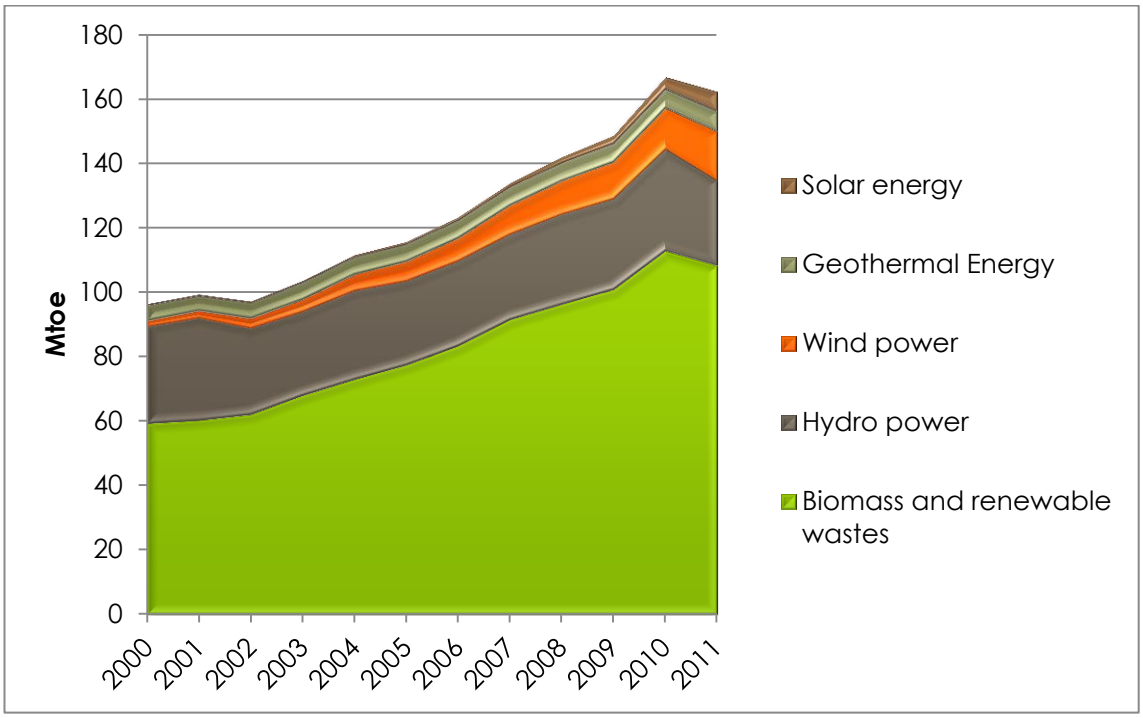

Figure 3. The progress of the primary production of renewable energy in EU 27-countries between 2000 and 2011. [9]

The world's total primary energy supply (TPES) and total final consumption (TFC) in 2010 are presented and compared with the values back in 1973 in Figure 4 and Figure 5, respectively. It can be seen that the absolute amount of consumed biofuels and waste has increased but their shares in the total final consumption has remained unchanged. The section "Other" in the figures include geothermal, solar, wind, heat, etc. The relatively low price of fossil fuels, their high energy density, and the easiness to process them have been the major reasons for their popularity as fuels in the past century. The awareness of the fossil fuels' polluting nature and the exhaustion of the reserves have however affected the willingness in replacing conventional energy sources with renewable sources. [8]

About 25% of the generated energy from biomass in the world is used in industrialized countries, where significant investments are made to meet emission standards. The other 75% is mainly used in developing countries for household heating, but also in biomass-based industries for process heat production. These plants generally use their own biomass residues as fuel. It is estimated that to stabilize the atmospheric CO_2 level, global emissions must reduce by 60% from the current level. Approximately 80% of total emissions are calculated to originate from burning fossil fuels. Much of the remainder 20% may be a result of deforestation, mostly in tropical regions. [10]

Biomass energy sources include wood and wood wastes, agricultural crops and their waste byproducts, municipal solid waste, animal wastes, waste from food processing, and aquatic plants and algae. Wood and wood wastes are the most common biomass sources in energy production (64% of total energy produced from biomass in the world). Municipal waste stands for 24%, agricultural waste for 5%, and landfill gases for 5%. [11]

Biomass is available in most countries and it can be used as feedstock in the production of solid, liquid or gaseous biofuels. As a renewable source it brings a more secure ener-

gy supply for countries. Biomass has also a large unused energy potential worldwide. The estimated annual energy potential and the current utilization of biomass in energy production are presented in Table 1. Only 38% of the world's available energy potential in biomass is utilized, mainly in Asia. For example in Europe it is theoretically possible to use four times the current amount of biomass for energy production. Only in Asia the energy use of biomass is non-sustainable. There, the yearly usage exceeds the rate of new biomass which is formed. [2] [8] [10]

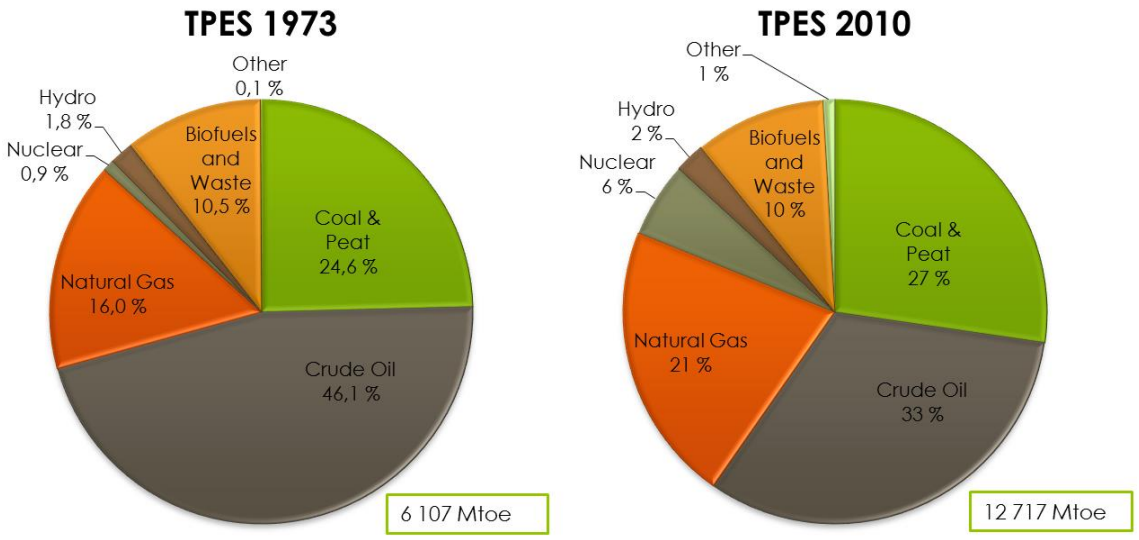

Figure 4. The world's total primary energy supply in 1973 and 2010. [1]

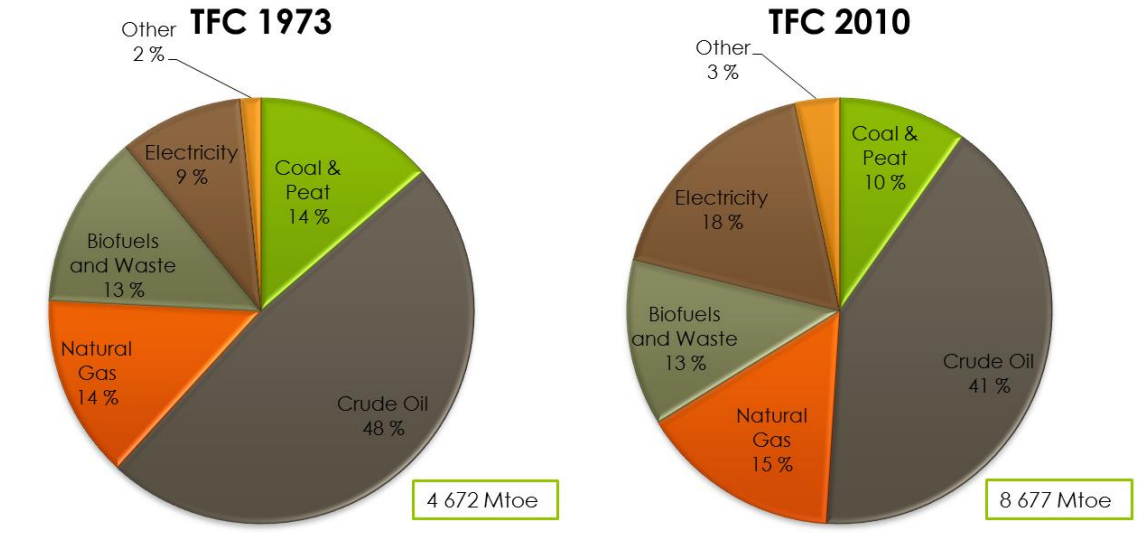

Figure 5. The world's total final energy consumption in 1973 and 2010. [1]

Table 1. The usable potential of biomass as energy source and the current use in different parts of the world in Mtoe per year. [10]

Biomass potential (Mtoe/a)	*North Amer.*	*Latin Amer.*	*Asia*	*Africa*	*Europe*	*Middle East*	*Former USSR*	*World*
Woody biomass	306	141	184	129	96	10	129	993
Energy crops	98	289	26	332	62	0	86	893
Straw	53	41	236	21	38	5	17	411
Other	19	43	64	29	17	2	7	181
Total potential	475	513	511	511	213	17	239	2 479
Current use	74	62	554	198	48	1	12	949
Use/potential (%)	16	12	108	39	22	7	5	38

2.2 Biomass properties

Biomass is characterized by its high moisture content, low bulk energy density, hydrophilic nature, and non-friable character. The high moisture content together with the high oxygen content reduces the heating value and energy density of biomass. The fibrous structure of wood increases the strength of the material, and thus complicates the crushing and size reduction of the particles required prior to combustion. These properties are discussed further in this chapter. [4]

2.2.1 Composition

The main components in wood are cellulose, hemicellulose and lignin. Together these form a matter called lignocellulose. The proportions of the components in lignocellulose vary depending on plant species. Moreover, biomass contains water and small amounts of extractives, proteins and inorganic matter. The extractives are organic substances with low molecular weight, such as resin, fats, waxes, fatty acids, alcohols and terpenes. In trees, the bark contains a higher concentration of extractives than the wood. [3] [8] [11]

On an extractive-free basis, the cellulose content typically ranges from 45% to 50% in softwood and 40% to 55% in hardwood. The hemicelluloses comprise 25-35% and 24-40% of the dry mass in softwoods and hardwoods, respectively, and the lignin 25-35% in softwoods and 18-25% in hardwoods. The extractives content typically ranges from 1% to 5% of the dry wood mass. [6] The proportions of the contents in spruce, pine and birch are compared in Table 2.

Table 2. Composition of different wood species in weight-% on dry basis. [6]

	Wood Species		
Component	*Spruce*	*Pine*	*Birch*
Cellulose	43	44	40
Hemicelluloses	27	26	39
Lignin	29	29	21
Extractives	1.8	5.3	3.1
Protein	1.3	1.2	2.5
Inorganic Matter	0.4	0.4	0.3

The cellulose and hemicelluloses are constructed from different sugars and they form macromolecule chains, i.e. the wood fibers (Figure 6). The lignin consists of aromatic polymers and it acts as a filler material which binds the fibers together. Cellulose is the main component and structural element in the cell walls of trees and plants. The cellulose is a linear polymer with high molecular weight. Hemicelluloses are less complex and easily hydrolysable molecules. They comprise a mixture of various polymerized monosaccharides. Lignins are highly branched aromatic polymers in the cell wall. The lignin gives the plants much of their strength, rigidity and brown color. The structure of lignocellulose in a plant's cell wall is illustrated in Figure 6. [3] [5] [11]

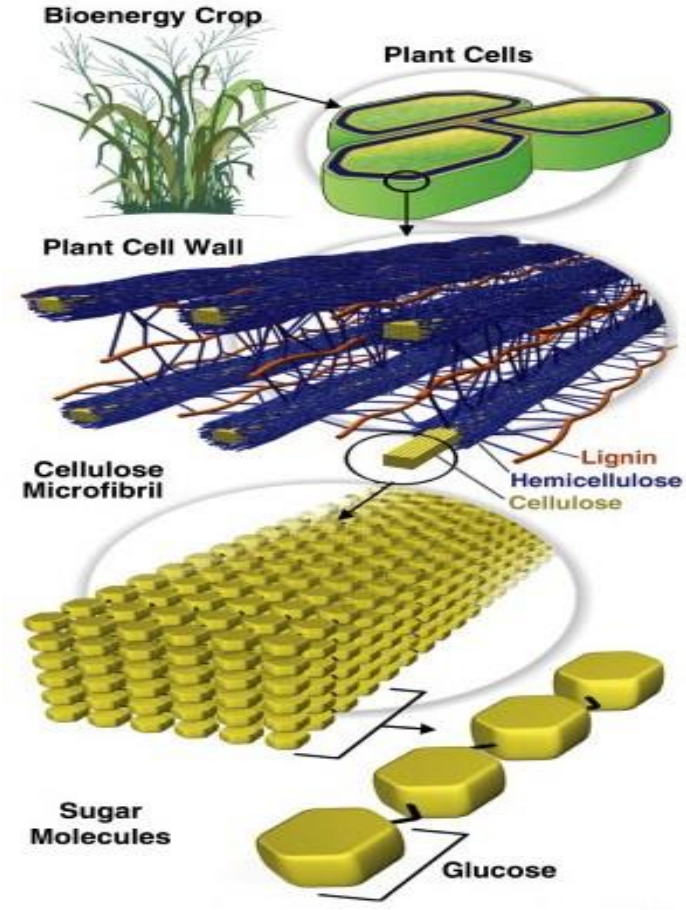

Figure 6. The structure of lignocellulose in cell walls of plants. [12]

Lignin has higher heating value than cellulose and hemicellulose, mainly due to its lower degree of oxidation and higher concentration of carbon and hydrogen. This is why the heating value of lignocellulosic materials strongly correlates with the concentration of lignin. This can be seen from the values in Table 3, where the relation between lignin content and the heating value of different biomaterials are presented. [3] [8]

Table 3. The relation between lignin content and heating value in different biomass fuels. [3]

Type of biomass	*Lignin (%)*	*Higher heating value (MJ/kg)*
Corn cob	15.19	17.99
Wheat straw	20.98	18.51
Hardwood	21.89	18.59
Softwood	32.55	19.53
Wood bark	44.13	20.57
Olive cake	55.29	21.57

The differences between softwoods and hardwoods are notable. Softwood usually contains much resin with high energy density. Due to the resin and the higher lignin content, the heating value in softwood is about 5% higher than in hardwood. The overall average density of softwood is however lower and the volumetric energy density is thus lower in softwoods than in hardwoods. Additionally, softwood has a tendency to burn up faster than hardwood. [5]

Hardwood generally grows faster than softwood but has shorter fibers compared to softwood. The longer fibers give the tree more strength. Softwood is thus more suitable as raw material in products where material strength is needed, such as paper and cardboard or as building material, while hardwood is more attractive as a fuel. [5]

The composition and properties of same type of biomass can vary considerably depending on location, season, etc. The average elemental composition and main properties of wood and other solid fuels are presented in Table 4. The concentration of oxygen is high in biomass, which is the main reason for the lower heating value of wood compared to coal. Other remarkable characteristics of wood are the low ash, nitrogen and sulfur contents, and the high volatiles content. These properties have an influence on the combustion and they affect the amount and composition of the emissions from combustion. More about the emissions and combustion of wood is discussed in Chapter 3. The volatiles contents in wood and coal are compared and discussed more thoroughly in Chapter 3.1.

Table 4. Average elemental composition and properties of different solid fuels. [3] [11] [13] [14]

	Unit	Coal	Peat	Wood	Wood pellet
Moisture	% (w.b.)	10	50	50	8
Element	% (d.b.)				
Carbon, C		75.6	52.4	50.3	49.4
Hydrogen, H		4.5	5.4	6.5	6.3
Nitrogen, N		1.2	1.8	0.5	0.3
Oxygen, O		7.2	35.1	41.1	43.4
Sulfur, S		1.3	0.2	0.03	0.03
Ash		10.2	5.2	1.5	0.6
HHV	MJ/kg	28.6	21.1	18.1	19.0
GHV	MJ/kg	25.2	9.6	8.9	16.9
Density	kg/bulk-m3	800	340	900	600

2.2.2 Moisture

The moisture content (MC) in matter is generally defined either on wet basis (w.b) or dry basis (d.b). In the wet basis definition, the mass of water in the material is given as percentage of the total wet weight of the material, while the dry basis definition is the mass of water related to the mass of dry matter. The formulas for calculating the moisture on wet basis and dry basis are presented in Equations (1) and (2), respectively. In this work, the moisture content of wood is generally defined on wet basis.

$$M_{wb} = \frac{m_w}{m_{dm}+m_w} \quad (1)$$

$$M_{db} = \frac{m_w}{m_{dm}}, \quad (2)$$

where M_{wb} is the moisture content on wet basis, m_w is the mass of water, m_{dm} is the mass of dry matter, and M_{db} is the moisture content on dry basis.

The moisture content in forest residues and by-products of the timber and carpentry industry may vary significantly depending on type, location, time of harvest and period of storage after harvest. Biomass collected from forests typically has moisture content in the range of 30-60% (w.b), usually around 50%. The wide range of moisture content causes operational problems, lowers the stability of burning and makes it difficult to control the combustion. [15] [16] [17]

Moist biofuels need higher amounts of excess air when combusted (60% for fuels with 65% moisture, while less than 20% for almost dry fuels), which decreases the adiabatic combustion temperature and efficiency. This can be seen in Table 5, where typical combustion values for wood with different moisture contents are presented. High mois-

ture content also increases the necessary residence time of the fuel in the combustion chamber, which has a negative effect on the combustion quality. When burning moist fuels, the specific amount of flue gas, and the content of carbon monoxide (CO) and volatile organic compounds (VOC) in the flue gas, are increased. This occurs mainly in smaller combustion units. [4] [16] [18]

Table 5. The dependence between the moisture content and the combustion properties of biomass. [18]

Moisture content	**%**	**65**	**50**	**15**
Water amount	kg/kg	1.9	1	0.2
Excess air level (anticipated)		1.6	1.4	1.2
Higher calorific value	MJ/kg	20.6	20.6	20.6
Lower calorific value	MJ/kg	14.4	16.5	18.6
Flue-gas volume (1 bar, 0°C)	m3/kg	10.3	8.8	6.2
Flue-gas loss (sensible heat)	MJ/kg	2.1	1.8	1.3
Efficiency based on higher value		0.6	0.71	0.84
Efficiency based on lower value		0.85	0.89	0.93
Adiabatic combustion temperature	°C	900	1200	1800

The formation of emissions in larger scale combustion units is less sensitive to the moisture content in the fuel. Here, to ensure sufficient combustion quality, the moisture content in the fuel has to be maximally 60-65% (w.b). Higher moisture content requires a support fuel to keep the adiabatic combustion temperature high enough. To ensure high gas quality in gasification processes, the moisture content in the biomass should not exceed 10 to 15%. [4] [16] [18]

When dry fuel is used and higher temperatures are reached, the capacity of existing boilers is increased. Also, when installing new boilers, the required size is decreased and the costs may be reduced if the boiler is designed for dry fuels. In addition to technological reasons, drying of biomass is important also due to transportation and storage reasons. The extra water in moist biomass brings dead weight and thus increases the energy needed for transportation. During long-term storage, the high moisture content support populations of fungi, which may cause allergic reactions in humans. The moisture also support microbiological processes which degrade the wood-fuel and can cause spontaneous ignition in the piles. [18]

The moisture in biomass exists in two forms: as free water and as bound water. The free water is located within the pores and on the outer surfaces of the material, while the bound water is bonded to the hydroxyl groups in the biomass structure. In wood, such hydroxyl groups are found in the major constituents, i.e. in cellulose, hemicellulose and

lignin. Higher specific energy is needed to evaporate the bound water than free water. [19] [20]

The specific heat needed to evaporate water from wet biomass fuel depends on the initial and final moisture contents, and the temperature of drying. The heat of vaporization of free water as a function of temperature can be approximately defined using the following equation:

$$l_w = 2501 \frac{kJ}{kg} - 2.43 \frac{kJ}{kg \cdot °C} \cdot T \,, \tag{3}$$

where l_w is the heat of evaporation [kJ/kg] and T is the initial temperature [°C].

[20]

The minimum heat of vaporization is thus 2 258 kJ/kg_{H2O} at 100°C. However, due to the bound water in biomass, the specific heat of vaporization may exceed 2 600 kJ/kg_{H2O}. Hence, the moisture in the fuel reduces the residual energy remaining in the fuel after the water is evaporated. The residual energy can be calculated using Equation 4, and it is presented graphically in Figure 7 as a function of the moisture content. [16] [20]

$$\mathrm{Q_{resid}} = 100 \left[1 - \frac{l_w M_{wb}}{(1 - M_{wb}) Q_{HHV}}\right], \tag{4}$$

where Q_{resid} is the residual energy [%], l_w is the heat of evaporation [MJ/kg], M_{wb} is the moisture content in the fuel on wet basis, and Q_{HHV} is the higher heating value of the fuel [MJ/kg].

[21]

In most combustion systems, the flame stability becomes poor when the MC exceeds 50-55% (w.b), and the limit when the flame is no more self-sustaining is reached at the level of 70-80% (w.b). As can be seen from Figure 7, the energy needed to vaporize water from most biomass species exceeds the heating value when the moisture content is over 90%. [21]

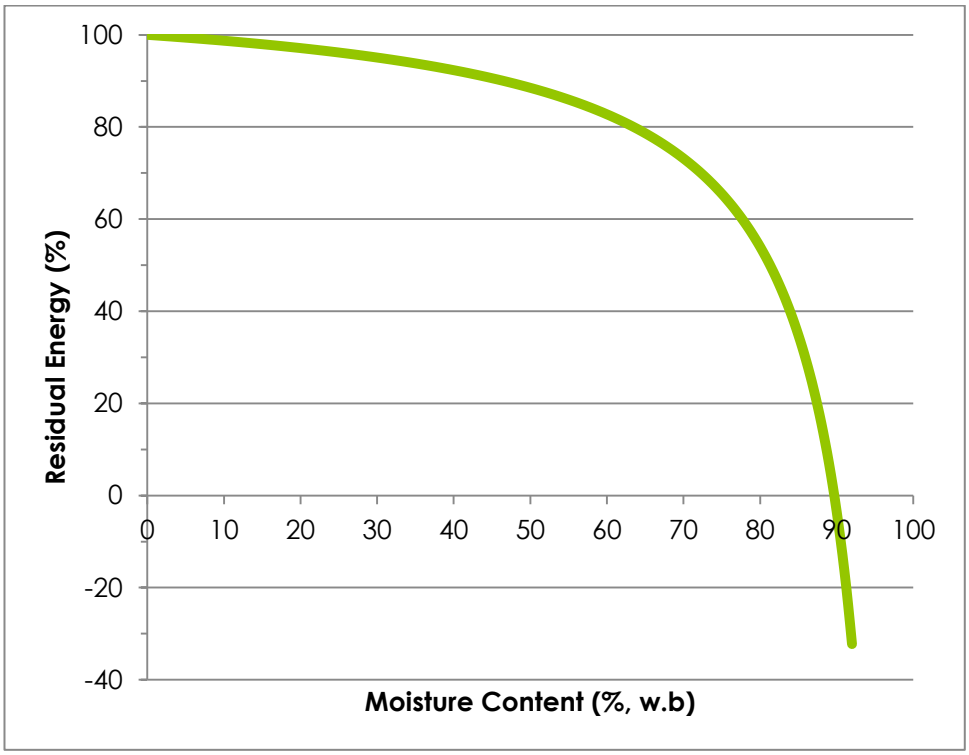

Figure 7. The residual energy of a fuel as a function of the moisture content. The residual energy is calculated with Q_{HHV} = 20 MJ/kg and l_w = 2,3 MJ/kg.

2.2.3 Storage

An important part of the supply chain is the storage of the biomass fuel. The way how the biomass is stored longer periods has a significant effect on the quality and properties of the fuel. As mentioned in the previous chapter, the moisture causes degradation processes in the material. Up to 1% of the biomass material is assumed to be lost per month due to the degradation during storage. [22]

The biological activity in the moist biomass during storage can be minimized in several ways. Firstly, by storing the fuel in larger pieces, the relative surface area where biochemical reactions occur, is reduced. Secondly, by using fungicides and other chemical agents, the biological activity can be prevented. Third method is to dry the biomass before storage to moisture contents below the level where the microbial activity is high (around 20% moisture on wet basis). Finally, the biological activities are slowed down if the biomass is cooled during storage. [19]

Because of the relatively low energy density, storing biomass requires wide spaces. Power plants located in populated areas usually have limited room for storage. Together with the great need of transportation capacity to the plant, the storage requirements are the major obstacles of using biomass as fuel in power plants. [3] [22]

The storage of the biomass fuel can be carried out on several locations. The storage on the field where the biomass is gathered is relatively cheap, but the land may not be available for long periods if new cultivation is desired there. In addition, the moisture reduction is not possible to be controlled to a required level, which may result in material losses and health and safety problems. [3]

Another alternative is to store the biomass on intermediate storage locations between the fields and the end using facility (power plant). This causes though higher total transportation costs due to the need of transportation twice over – first between the field and the storage facility, and secondly between the storage facility and the power plant. The additional transportation and handling costs are estimated at 10-20% when using intermediate storage facilities. [3]

The storage of the fuel next to the biomass power plant (Figure 8) is beneficial due to the excess heat usually available from the plant for the drying of the fuel. The transportation costs are higher than with on-field storage though, because of the dead weight of the higher amount of water in biomass. [3]

Figure 8. Porvoon Energia biomass power plant in Tolkkinen, Porvoo.

2.3 Pretreatment methods

The main drawbacks when using biomass as a fuel are related to the transportation. Because biomass is widely spread in the nature, the collecting usually requires much work. Also the high moisture content and low energy density of the fuel increase the transportation costs. To ease the handling of biomass and to improve its combustion properties, the biomass has to be pretreated.

The main pretreatment methods prior to combustion are sizing (grinding, chipping, chunking, milling, etc.) and drying. To increase the energy density of biomass, pretreatment methods such as pelletizing, briquetting and torrefaction are used. During collection and handling of trees, soil particles are stuck into the bark. To reduce the ash formed from the soil during combustion, the wood need to be washed before processing. [19]

The pretreatment requirements are defined by the end use of the biomass. If fired together with pulverized coal, size reduction of wood is necessary to meet similar combustion properties. The particles size has to be decreased to less than 4-5 mm. Due to the fibrous nature of wood, the equipment designed for coal milling, such as ball-race mills, roller mills and hammer mills, have difficulties to crush untreated wood. In addition to the sizing requirements, the transportation costs can be decreased if the energy density is raised by pretreatment methods. [19]

Wood pellets

In wood pellets (Figure 9), particles are compressed together into cylindrical shapes with the diameter of 6-10 mm and length of 10-30 mm. The pellets have relatively high energy density due to their compactness and low moisture content (around 10%, w.b). They are friable and thus suitable for combusting in pulverized coal-firing plants. The round and smooth shape simplifies the transfer and feeding of the pellets, and due to the homogenous shape and properties of the pellet, the fuel suits well for automatic feeding systems. [4] [16] [23]

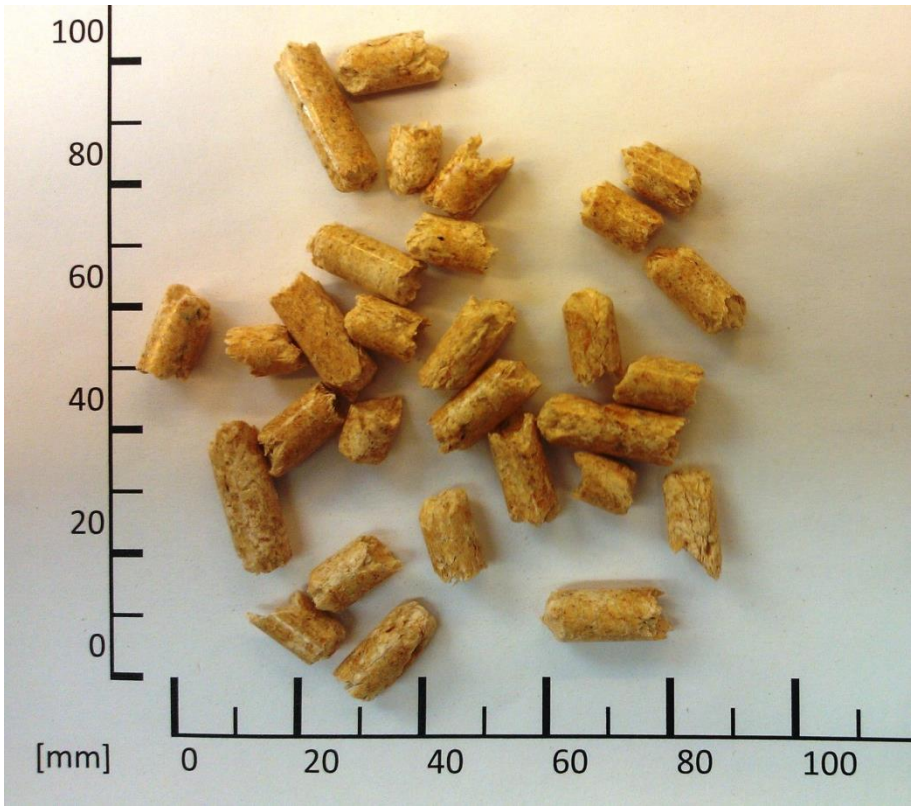

Figure 9. Wood pellets.

By-products from the mechanical wood processing industry, mainly sawdust or planer shavings, are used as raw materials in wood pellet production. As the demand for pellets increases, the supply of dry sawdust becomes insufficient and other raw materials with lower value and higher moisture content have to be used. If the particles in the material are too large or too moist, the material has to be ground and dried before processing. The required particle size is less than 4 mm and moisture content 8-15% (w.b). To remove oversized particles, the material is screened. [13] [24] [23] [25]

Wood pellets are produced by pressing the shavings or dust through holes of a die by rollers. During compression, eventually with assistance of external heat, the wood warms up to 160-175°C and the lignin in the wood starts to dissolve. When cooled, the lignin hardens and binds the material together, and the pellets become compact and their surface smooth. [24] [23] [26]

Torrefied biomass

By torrefying biomass, more coal-like properties can be reached to the fuel than by pelletizing. In torrefaction, the biomass is treated thermo-chemically in absence of oxygen at temperatures between 200 and 300°C for residence times of 30-60 minutes. As a result, the water and volatiles are released from the biomass and it becomes friable and hydrophobic. [4] [13]

About 10% of the energy content in the biomass is lost with the released volatiles. The volatiles can however be captured and utilized as fuel for the torrefaction. As a result, the heating value of the biomass can be increased by 10-22% as the moisture is removed, but the bulk density is decreased and the volumetric energy density remains low. The torrefied biomass can though be further pelletized to densify the fuel. [4] [13]

3 Combustion of biomass and coal

To reduce the CO_2-emissions from fossil energy sources, the usage of coal as fuel in power plants has to be reduced and substituted by renewable sources. One alternative is to replace coal with biomass either in new plants designed especially for biomass, or in already existing coal-fired plants by co-firing. The term co-firing means burning more than one type of fuel simultaneously. [4]

The similarities between coal and biomass properties allow them to be handled and burned with similar techniques. Due to their lower requirements for the fuel, fluidized bed boilers are usually more suitable for biomass combustion than for example pulverized fuel fired boilers. Coal is though normally burned in pulverized fuel boilers. The investments required to modify existing plants to burn biomass together with coal are in general small compared to the investments needed for building new plants for biomass alone. In some existing plants it is possible to burn small amounts of biomass together with coal even with no modifications at all. [4] [6] [19]

In this chapter, the properties of wood and coal are compared and discussed together with the characteristics of wood combustion. Furthermore, the present methods for co-firing wood with coal are presented and discussed, and the principles of pulverized fuel firing are explained in this chapter.

3.1 Wood and coal comparison

Coal and wood fuels differ from each other in both chemical and physical properties, but the combustion behavior of wood is though generally comparable with the behavior of low-rank coals. The differences in the compositions between coals and wood can however cause troubles in the boiler systems. In addition to the difficulties with milling wood described in the previous chapter, the different composition of the fly ashes exposes the heat exchanger surfaces to increased deposits. [3] [13]

Coal is a sedimentary organic rock that contains more than 50 % carbonaceous material by weight. It is a fossil fuel because it is formed from plant material which grew millions of years ago, and was buried by sediments when the land subsided. The high pressures and temperatures have processed and altered the plant remains over long periods of time. The percentage of carbon has increased over the time, resulting in formation of different ranks of coals depending on their age. Older and higher rank coals are the anthracite and bituminous coal, while the subbituminous and lignite are classed as lower rank coals. Peat is a precursor of coals, as it is significantly younger than lignite. The typical properties of different coals and peat are compared in Table 6. [27]

The typical volatiles and fixed carbon (char) contents in wood and coal are presented in Table 7. Wood has significantly higher volatile matter content and lower fixed carbon content than coal. The ratio between volatile matter and fixed carbon in biomass is typically over 4, while it is in coal almost always below 1. The combustion characteristics are strongly dependent on the volatiles/char-ratio. [28]

Due to the high volatiles content, the ignition of wood fuels is easier and more homogenous than of coal. Also the combustion of volatiles is faster than of char. Additionally, the char from woody biomass is more reactive than the char from coal, and complete combustion is thus easier to achieve with wood. However, the significantly higher mois-

ture content in fresh wood decreases the combustion quality. So without fuel preparation, the combustion advantages are not reached. [3] [7] [13] [28]

Table 6. The compositions of different the coal grades and peat. [29]

Proximate Analysis (wt.-%, as received)	*Anthracite*	*Bituminous Coal*	*Subbituminous Coal*	*Lignite*	*Peat*
Fixed Carbon	67-84	40-77	33-47	32	13
Volatile Matter	2-11	17-40	30-32	27	35
Moisture	2-5	1-12	14-31	37	50
Ash	10-20	3-12	4-7	4	2
Heating value (MJ/kg)	33	29	20	17	11

Table 7. Volatiles and fixed carbon content in wood and coal. [3] [14] [30]

	Volatile content (wt.-%, d.b)	**Fixed carbon content (wt.-%, d.b)**
Wood	70-82	13-29
Coal	27-34	38-63

The volumetric energy density of fresh wood is low, mainly because of the moisture. With pretreatment methods described in Chapter 2.3, the energy density can be increased to the same level as lower ranked coals. The bulk energy densities between coal and different pretreated wood products are compared in Table 8. [13]

Coal has higher heating value mainly due to the lower oxygen content compared to wood, but also due to the different chemical structures between coal and wood. The amount of energy bound into the carbon-carbon bonds, which are more common in coal, is higher than the energy in carbon-hydrogen and carbon-oxygen bonds. The oxygen, however, increases further the thermal reactivity of the wood fuel. [4] [28]

The concentrations of sulfur (S) and nitrogen (N) in wood and coal are presented in Table 4. It can be seen that the contents of sulfur and nitrogen are substantially lower in wood than in coal. Harmful sulfur and nitrogen oxides (SO_x & NO_x, respectively) formed from the fuel are thus reduced when substituting coal with wood. Eventually no expensive SO_x-reduction techniques are needed when burning woody biomass alone. The SO_x- and NO_x-emissions are the major causes of acid rain. [5] [13] [28]

Also the ash contents of solid fuels are presented in Table 4. The lower content of inorganic elements in wood results in reduced ash formation when burned. The need of ash removal capacity is thus lower for wood. Furthermore, the elemental composition of the ash from wood differs from the composition of coal ash. This has an effect on the deposit formation in the boiler system. In addition, the possibility of using the ash further as construction material is affected by the different composition. More about the ash is discussed in the following chapter. [13]

Table 8. The bulk energy densities of coal and different wood products. [13]

Fuel	*Energy density, MWh/bulk-m ^{3}*
Coal	5.5-6.0
Wood pellets	2.5-3.0
Wood chips	0.72-0.78
Chipped forest residues	0.8-0.85
Sawdust	0.5-0.6
Bark chippings (pine)	0.45-0.5
Bark chippings (spruce)	0.55-0.65
Bark chippings (birch)	1.1-1.3
Cutter shavings	0.4-0.5
Straw chaff	0.25-0.35
Torrefied biomass	1.28
Torrefied pellets	3.9-5.14

3.2 Combustion & ash

Before igniting, the fuel has to be gasified. Heat releases volatiles from the wood during gasification, and combustion occurs when these volatiles react with oxygen in air. The combustion forms a chain reaction when the formed heat releases new volatiles from the fuel. The main combustion reactions are the oxidation of carbon to carbon dioxide, and hydrogen to water. [3] [8]

If left in the nature or in landfills, the decomposing biomass releases harmful compounds to the environment, including methane (CH_4), ammonia (NH_3), hydrogen sulfide (H_2S), amides and volatile organic acids. Methane is calculated to be 21 times more harmful greenhouse gas than CO_2. By recovering and combusting the biomass, the emissions of these pollutants are reduced. [3] [19]

The rate of combustion is affected by the moisture content and particle size. The moisture absorbs great amounts of heat when vaporized and lowers the flame temperature, as mentioned earlier in this work. The combustion of smaller particles is faster due to their larger specific surfaces where reactions take place. Biomass combustion is discovered to occur in two main steps at different temperature levels. At the first step, the light organic volatiles are released and burned, largely by pyrolysis of hemicellulose and cellulose, but also partly of lignin. The second step is characterized mainly by char oxidation. Coal combustion is though characterized by only one step, but it is however clearly wider than the steps in biomass combustion. [13] [28]

As the concentrations of elements in biomass vary greatly, also the elemental content in the ash and the amount of ash vary widely between different species and growth media. The average shares of ash in common solid fuels are presented in Table 9. The lower ash content reduces the capacity needed to remove ash when burning biomass, but the different elements especially in the fly ash, can cause more problems in the boiler.

The major constituents in the ash from coal and peat are silicon (Si), aluminium (Al) and iron (Fe), while the biomass ash mainly consists of alkali- and earth alkaline metals,

such as calcium (Ca), magnesium (Mg) and potassium (K). The concentration of sodium (Na) in biomass is generally low, unless the wood logs are stored in salt water. Wood bark can be rich in Si, if much sand and soil particles are stuck in the bark during the logging and handling process. [5] [6] [31]

Coal ash can also contain great amounts of Ca, but it originates generally from the adding of limestone into the furnace to control sulfur emissions. Also the trace and heavy metal concentration (such as mercury and lead) in biomass is minimal compared to the concentration in coal. The amount of toxic emissions in the flue gas from biomass is thus lower and the need of flue gas cleaning is reduced. [5] [6] [31]

Table 9. Average ash contents in different fuels. [3] [11] [13] [14]

Ash content in different fuels (wt.-% on dry basis)				
Wood (without bark)	Wood (with bark)	Wheat straw	Peat	Coal
0.4-0.5	1.7-2.7	4.7-14.2	4.0-7.0	8.5-10.9

The alkaline metals in the biomass are generally part of organic molecules or dissolved as ions in the cell fluid. These metals are thus more easily released in the flue gas during combustion than the metals in coal and peat, where they are in a more stable form. The alkaline metals in the flue gas are usually responsible for fouling of heat transfer surfaces. [3] [4] [13] [31]

The ash melting behavior and the deposit formation in the boiler depend on the elemental composition of the ash. The alkaline metals form compounds with low melting points (below 700°C) in the boiler. When these compounds collect on surfaces in the boiler, they form a sticky layer which enhances the ash deposition and fouling. Because biomass fuels contain in general higher amounts of alkaline metals compared to coal, the fouling and corrosion problems are more significant when burning biomass. The deposits formed from biomass combustion are harder to handle, because they form a tougher, smoother and less porous layer on surfaces. Additional cleaning techniques may thus be required when burning biomass instead of coal. [3] [4] [13] [19]

The chlorine (Cl), which is a constituent in all biomass, forms compounds with alkali metals such as potassium chloride and sodium chloride (KCl and NaCl, respectively). These alkali chlorides are the major corroding elements in the flue gas. Even a small amount of Cl in the fuel can be harmful for the heat transfer surfaces in the boiler system. The problems with chlorine are significant when burning wood alone or when the proportion of wood in co-firing is high. When the wood is fired together with coal or peat, the high amounts of sulfur and aluminium silicates in coal and peat react with and bind the harmful alkali- and chlorine compounds, and the problems with the deposits and corrosion decrease in significance. Also the SO_x- emissions from coal and peat decrease when the sulfur remains in the ash. Instead, the slag formed from co-firing is more harmful than from coal alone. [3] [4] [13] [19]

3.3 Co-firing with coal

3.3.1 Co-firing techniques

Three general co-firing techniques are used when burning biomass together with coal. The principles of these options are shown in Figure 10. The first option is direct co-firing, where biomass is mixed with coal and the mixture is burned in the same furnace. The second method is called indirect co-firing. It involves gasification of the biomass prior to feeding into the same furnace with coal. The third method is parallel co-firing, where the biomass and coal are combusted in separate burners and boilers. The steam produced in each boiler is linked into same steam network. [3] [4] [13] [19] This work will concentrate only on the direct co-firing.

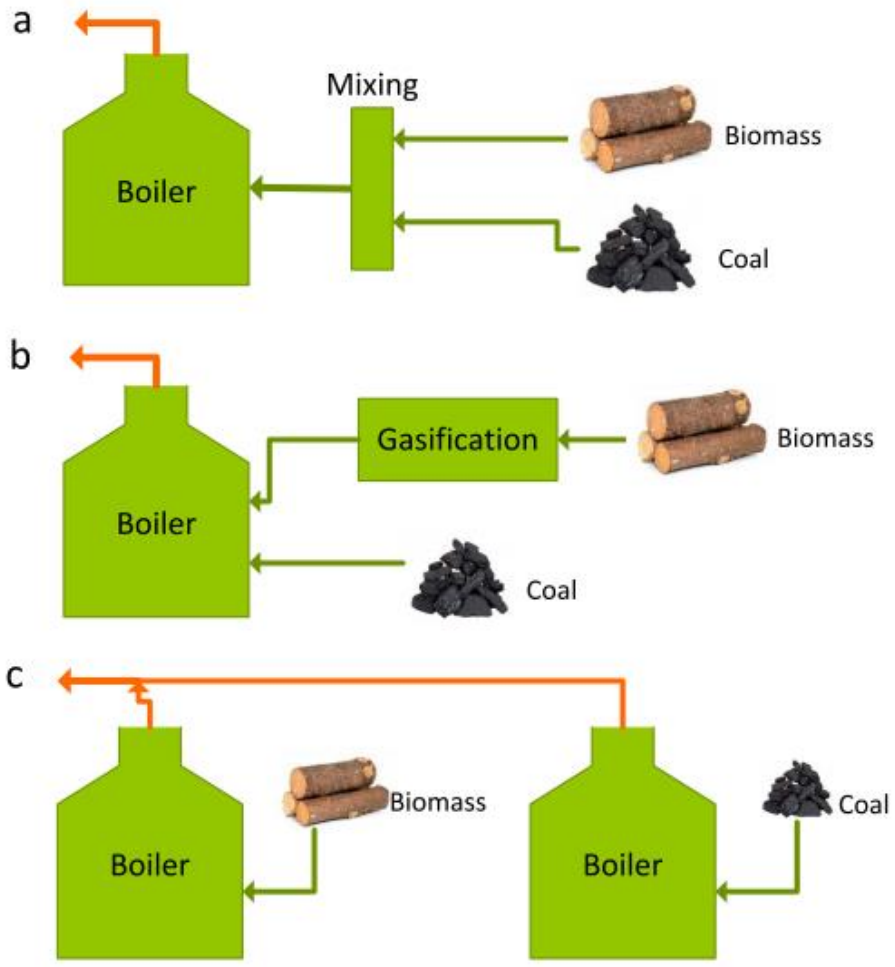

Figure 10. Main biomass and coal co-firing technologies; (a) direct co-firing, (b) indirect co-firing, and (c) parallel co-firing.

The direct co-firing in pulverized fuel firing boilers is the most common and straight-forward configuration and can be carried out in three different ways [3] [4] [13] [19]:

1. The simplest and least expensive way is to mix the biomass with the coal prior to the pretreatment equipment. The fuel blend is processed through the same coal milling and firing system.

2. The second option involves separate pretreatment apparatus for the biofuel. The processed biomass is injected into the pulverized coal line before or in the burners and thus fired with the same burner.
3. In the third method, the biofuel is, in addition to separate handling and pretreatment, also combusted in separate burners in the same furnace. Significant modifications involving high capital costs are needed to the furnace and combustion system in this method. It is though possible to use biomass as a reburn fuel in NO_x-emission control, if it is injected into the upper parts of the furnace.

The indirect and parallel co-firing configurations allow higher fuel flexibilities than the direct co-firing method. Additionally, the gasification gas in the indirect system can be cleaned prior to combustion to increase the combustion quality and to decrease formation of harmful compounds. The parallel firing system is the most expensive alternative, as it requires a separate boiler system for the biomass. [13] [19]

Several types of boilers are used for biomass combustion, such as grate-fired and fluidized bed boilers. The circulating fluidized bed (CFB) boilers are becoming more popular due to their lower demand on the fuel quality. CFB-boilers are able to accept higher moisture contents and wider variations in the fuel blend. For coal-firing, the combined heat and power (CHP) plants in Finland mainly operate with pulverized fuel firing techniques. Only the newest bigger plants are built with CFB-boilers. The principles of these combustion techniques are represented in Figure 11. [6] [13]

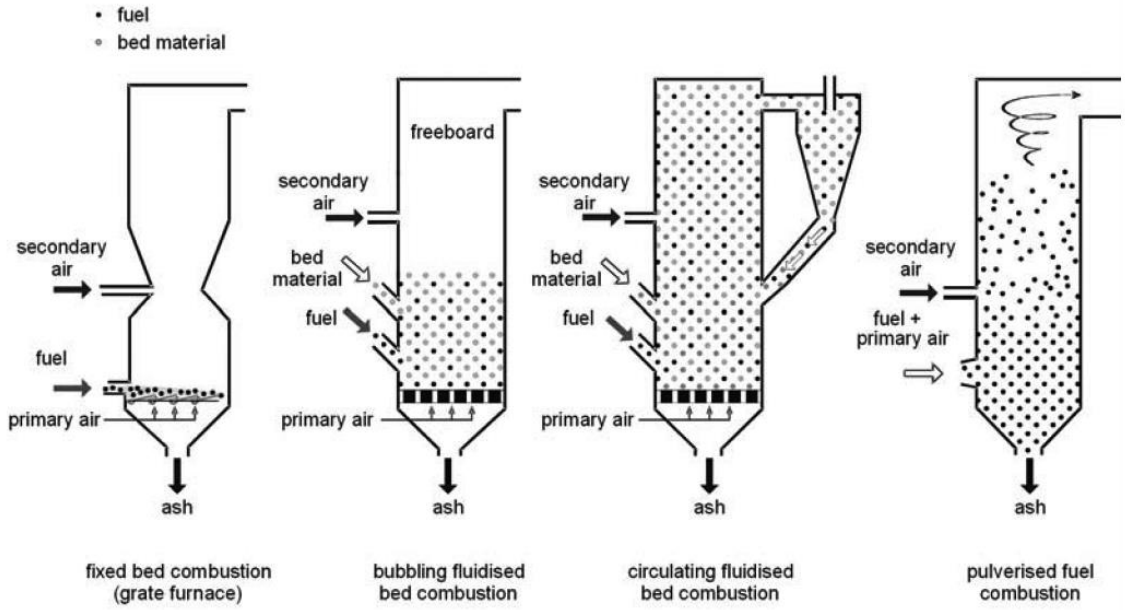

Figure 11. Principal combustion techniques for biomass. [19]

3.3.2 Impacts

In co-firing with coal, the proportion of biomass in the fuel generally ranges from 1% to 20% on input energy basis, typically between 5 and 10%. Low proportions are possible to be burned without any needs of modifications in the plant. With new pulverized coal firing units, where modifications are done to the burners, dryers and mills, it is possible to use a fuel blend with a biomass share up to 40%. [4] [21]

When co-firing in plants designed for burning coal alone, the proportion of biomass in the input fuel is mainly limited by the following factors: Firstly, as mentioned in the previous chapter, the high alkali and chlorine contents in biomass increase the formation of deposits and risk of corrosion on surfaces in the boiler system.

Secondly, the different constituents in the ash from biomass and coal change the composition and properties of the ash formed during combustion. As a result, the ash quality may not meet the requirements set for ash used as construction material, which may lead to higher costs of ash disposal. To prevent the undesired changes in the ash composition, the share of biomass ash in the total ash is generally limited to 10%, and the share of biomass in the fuel input is thus limited to 20% (on energy input). [3] [13]

Thirdly, due to the large amount of evaporating moisture, the quantity of flue gas is significantly increased and its temperature is decreased when burning moist biomass. Hence, the load and the energy consumption of the flue gas blowers are increased, and the optimal plant operation conditions can be affected by the different flue gas values. Additionally, the erosion of surfaces increases with increasing flue gas volumes. [6] [13]

Different researches have given different results about how coal and biomass affect each other during combustion, so no unambiguous conclusions can be drawn about possible interactions between the fuels when co-fired, except for the reactions between the different ash components. The use of wood as co-firing fuel in coal-fired boilers has shown to cause no decreasing effect on the boiler capacity, and only modest efficiency losses. The fly-ash particles formed from biomass in co-combustion are though observed to be significantly smaller than those formed in coal combustion, which may result in increased particulate emissions. [6] [19] [28]

The implementation of biomass as co-firing fuel might involve increased variable costs for the plant, mainly due to the increased need of service and maintenance caused by the deposit. Although there might be more problems when burning biomass, the substitution of coal with renewable fuels is usually reasonable, due to the additional costs and taxes set to fossil fuel firing. The additional costs with the biomass use in coal-fired boilers are assumed to be in the range of 1-5% of the total operating costs, depending on the properties and share of burned biomass. These costs are however generally lower than the savings involved in reduced fossil fuel usage and emission costs. [13]

The main advantages of co-firing biomass with coal are the following:

- Coal can balance the combustion by reducing effects of biomass quality fluctuations.
- If the availability of biomass is insufficient, coal can be used in increased amounts to meet the energy demand.
- The costs of modifying an existing power plant to be suitable for co-firing are lower than the costs of building new systems only for biomass combustion.
- By substituting coal with biomass, the amount of CO_2-emissions from fossil coal and also the amount of SO_x- and NO_x-emissions are reduced.

The barriers with adding biomass as a co-firing fuel to a coal power plant include the biofuels procurement issues, biofuel quality issues, ash quality issues, limiting maximum share of biomass in co-firing under given configurations, and the capacity limits of the plant logistics. [4] [6]

3.4 Pulverized fuel firing

In pulverized coal power plants the coal is powdered and blown together with the combustion air into the burners in the furnace. The heat released from the combustion vaporizes water and superheats the formed steam. The steam is led to a turbine, where the enthalpy of the steam is converted to kinetic energy as the expanding steam rotates the turbine. The turbine rotates a generator which produces electricity. This is illustrated in Figure 12. In CHP-plants the remaining heat in the steam after the turbine is recovered and used as process heat or for district heating. [13]

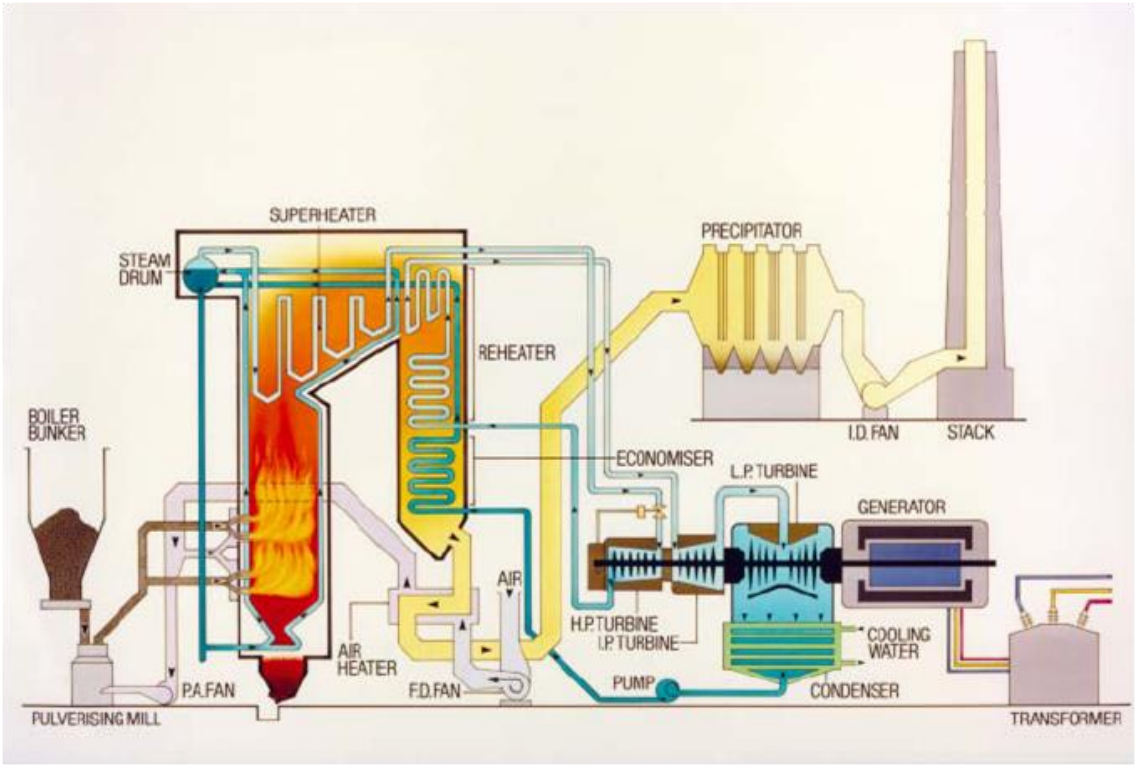

Figure 12. Layout scheme of a pulverized coal firing plant for electricity production. [32]

Several different combustion technologies are available for biomass combustion, such as fixed bed, fluidized bed and pulverized combustion. Pulverized fuel firing is usually associated with large scale coal combustion and it is the most common and widely used method for burning coal. It is rarely used for combustion of biomass alone, but co-firing of pulverized coal and biomass is becoming more common. Fluidized bed combustion is generally regarded as the best technology to burn a fuel with low quality, high ash content and low heating value. Untreated biomass does not normally meet the property requirements for burning in other than fluidized bed boilers. [3] [19] [33] However, in the DustComb-system the wood is assumed to be processed enough to meet the requirements for pulverized fuel combustion.

Three basic designs are used for pulverized coal firing. The wall-fired and tangentially fired boilers, where the flames are directed horizontally, are the most common types. The third type is the arch- or roof-fired boiler, in which the flames are directed downwards from the top of the boiler. The furnaces are usually equipped with several combustors to increase the burning efficiency. The construction of a wall-fired burner is presented in Figure 13. [33]

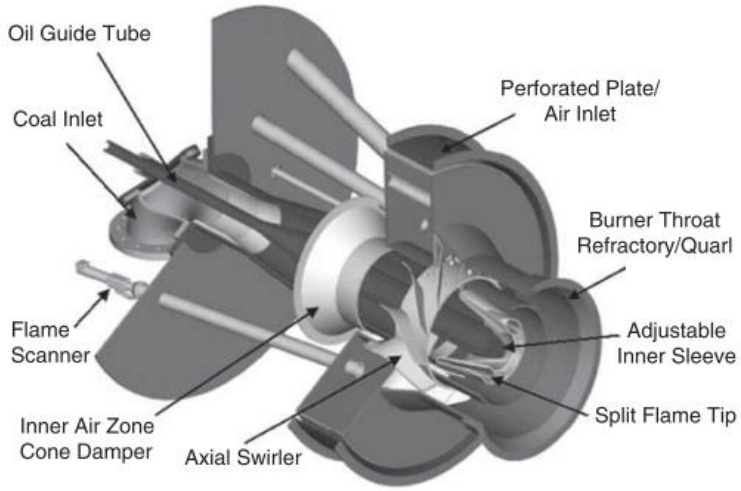

Figure 13. The construction of a Foster Wheeler wall-fired burner. [33]

The fuel powder is pneumatically transported with the combustion air from the grinder to the burner and into the furnace. To improve the combustion, the fuel and air stream is usually preheated to temperatures between 60 and 90°C, depending on the fuel type and moisture content. The preheating has to be carefully controlled, because too high temperatures in the fuel/air-stream before the burner increase the risk of autoignition and fires in the fuel preparation system. [29] [33]

The characteristics in pulverized fuel systems are the high peak flame temperature and the short residence times of the fuel (only a few seconds). When entering the furnace, the coal starts to release volatiles as it heats up. The coal ignites and starts to decompose at around 390°C. Due to the small particle sizes and the turbulent fuel and air mixing, the combustion is aggressive and the temperature rises rapidly. The flame temperature usually peaks around 1 600-1 650°C. [19] [33]

To increase the combustion quality and to minimize the emissions of harmful compounds, especially NO_x-emissions, the firing is usually staged. In stage-firing the combustion air feed is divided into multiple phases, i.e. into primary, secondary and eventually tertiary air. In swirl-stabilized burners (Figure 14), the primary air carries the fuel to the burner, which directs the fuel and air mixture into the furnace from the central parts of the burner. The secondary air, and eventually the tertiary air, is fed to the periphery of the primary flame. The secondary air swirls around the outside of the flame and thereby shapes and stabilizes the activity of the flame. The function of a wall-fired swirl-stabilized burner is illustrated in Figure 15. [33]

Figure 14. A swirl-stabilized wall-fired burner at Detroit Edison Company's Power Plant at Monroe, Michigan. The swirler plates for the secondary air can be seen on the periphery of the burner. [33]

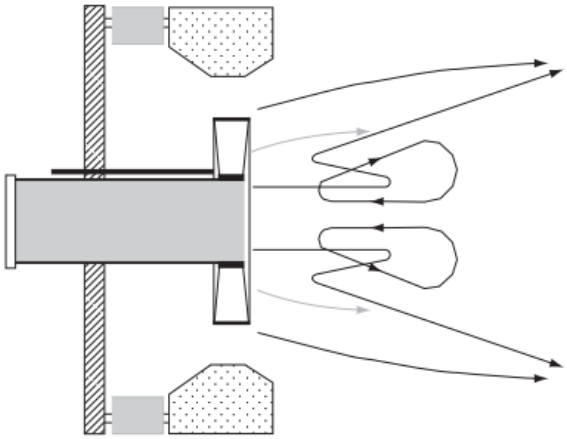

Figure 15. The operation principle of a wall-fired swirl-stabilized pulverized fuel burner. The fuel and the primary air are fed from the middle, while the secondary air is fed to the periphery of the flame. The secondary air creates recirculation zones in the center of the flame. [33]

Due to the limited residence time in pulverized fuel firing, the importance of particle size and density is significant. Large and dense particles tend to fall out of the flame due to the gravitational forces, and collect to the ash hopper as unburned material. Smaller, but dense particles may not burn completely due to the insufficient residence time in the flame. These particles leave the furnace as unburned fuel with the fly ash. In addition, if the particles do not have time to burn completely before leaving the furnace, the risk for over-heating and severe slagging and fouling is increased on the heat transfer surfaces in the flue gas ducts. [19] [29]

The particle size requirements for different coal types and biomass in pulverized fuel firing are listed in Table 10. For maximum performance efficiency, coal should generally be ground to a size where at least 70% of the particles passes through a 200-mesh screen (hole size 74 µm) and less than 1% is remained on a 50-mesh (300 µm) screen. [29] [33]

Table 10. The sizing requirements for fuel particles. [29]

Fuel type	As recieved size	Pulverized firing	CFB
		Distribution (<200 / <50 mesh)	Top size
Anthracite	<2"	80% / 99%	1/4"
Low volatile bituminous coal	<2"	75% / 99%	3/8"
High volatile bituminous coal	<2"	75% / 99%	1/2"
Subbituminous coal	<2"	65% / 98%	1/2"
Lignite	<2"	65% / 98%	1"
Herbaceous biomass	Varies	1/4"	2"
Woody biomass	Varies	1/4"	2"

The equipment used for fuel sizing employs at least one of the following main crushing methods: impaction, attrition, shear, and compression. In impaction, an object is either dropped (gravity impact) or accelerated by an outside power source (dynamic impact) to crush the fuel particles. Alternatively, the fuel is set to collide with a static surface. With dynamic impact, more homogenous particle distribution is received. [29]

In attrition, the fuel is rubbed between two hard surfaces and forced through a given clearance. The particular clearance makes sure that oversized particles do not leave the grinder. The attrition is usually used for friable materials. This method may be reasonable if it is not desirable to apply a closed circuit system, where oversized particles are sent back for regrinding. [29]

The shearing is a dynamic method of sizing and usually combined with other methods. The somewhat friable fuel particles are cleaved or cut, and the product is relatively coarse. The product from compression is also relatively coarse. Here, the fuel is ground between two compressing hard surfaces. This method is generally applied for hard and abrasive fuels. [29]

4 DustComb equipment

The process investigated in this work, where a mechanical defibrator is integrated with a flash dryer to produce wood fines, is called DustComb-process. The wood fines are produced from wood chips or forest residues, and they are meant to be burned in a pulverized firing boiler for energy production. In this chapter, the principles of the pieces in the DustComb, i.e. the mechanical defibrating and flash drying, are discussed separately.

4.1 Set-up of the DustComb

The operational principle of the DustComb-process is to combine a mechanical defibrator with a flash dryer prior to a pulverized firing combustor. Wood chips or forest residues are defibrated mechanically, and the formed fines are blown through the dryer to the furnace. The flow chart of the process is represented in Figure 16.

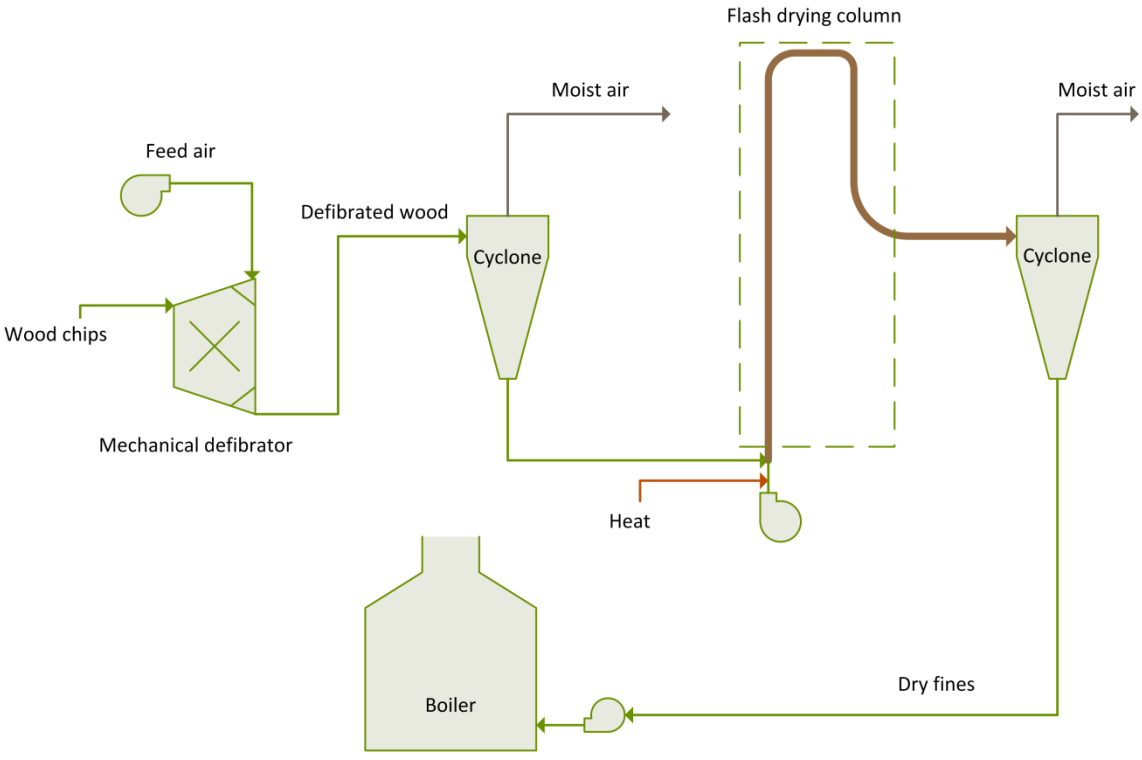

Figure 16. Flow chart of the DustComb-process.

The DustComb can either be integrated into the power plant process or operated separately from the boiler. In the latter alternative the fuel is stored into a temporary reservoir before burning. The energy needed for the wood processing can either be taken from the energy produced in the same plant or purchased as market electricity and heat. The defibrator is the major electricity consumer, but also the air blowers, which are needed for the transportation of the material through the process, use electricity. The dryer is the only consumer of heat, except for winter time when heat may be needed to melt the wood chips. Chip preheating is not assumed to be necessary if the chips are not frozen.

The source for the drying heat depends on where the system is situated. In power plants, the heat can be taken for example from the flue gas, condensate water, or in CHP-plants from the process steam. The amounts of electricity and heat needed in the DustComb-process are calculated, and the different energy sources are evaluated and compared in Chapter 6.

4.2 Mechanical pulping

The purpose of pulping is to separate the fibers from the wood matrix to be used for papermaking. The lignin and, to some extent, the hemicellulose are in mechanical pulping softened, while they are in chemical pulping dissolved to release the fibers from the binder. To soften the lignin in mechanical pulping, the wood is frequently strained by the forces caused by the grindstone or the bar pattern on the refiner discs. [34]

Two main techniques to produce mechanical pulp exist at industrial scale: Grinding, where wood logs are pressed against a revolving grindstone, and refining, where wood chips are broken up between two disc blades in a disc refiner. The type of pulping designed to be used in the DustComb process is refining (also called defibrating). This work will thus only concentrate on the refiner mechanical pulping (RMP), which is the simplest variety of the refining processes. The main mechanical pulping processes are listed and described briefly in Table 11. [34]

Table 11. Nomenclature for mechanical pulping processes. The shower water is fed into the pulper with the wood. [34]

Abbreviation	Process	Description
SGW	Stone Groundwood	Atmospheric grinding of wood logs against a grindstone. The shower water temperature is normally 70-75°C.
PGW	Pressure Groundwood	Wood logs are ground under pressurized conditions (2.5 bar) at shower water temperatures below 100°C.
PGW-S	Super Pressure Groundwood	Logs are ground under highly pressurized conditions (4.5 bar) at shower water temperatures above 100°C
TGW	Thermo Groundwood	Atmospheric grinding of logs at shower water temperatures of 80°C or higher.
RMP	Refiner Mechanical Pulp	Atmospheric refining of wood chips by a disc refiner. The chip pretreatment comprises only washing and possibly some atmospheric presteaming.
PRMP	Pressure Refiner Mechanical Pulp	As RMP, but supplemented with pressurized refining at an elevated temperature.
TMP	Thermomechanical Pulp	The chips are preheated with pressurized steam and refined under pressure at elevated temperatures. The steam pressure is normally 3-5 bar and its temperature correspondingly 140-155°C.
CMP	Chemimechanical Pulp	Common name for all pulps of this type. Pulp manufactured from chemically and normally also thermally pretreated chips by refining under atmospheric or pressurized conditions.
CTMP	Chemithermomechanical pulp	Pressurized refining of chemically pretreated chips or coarse pulp. Relatively mild treatments.

The main components in the defibrator are the disc blades, i.e. the rotating rotor and the static stator, which are installed in a housing covered by thick steel walls. In some varieties, both of the discs are rotating at opposite directions. Wood chips are fed into the gap between the discs from the opening in the center of the other disc (Figure 17). The revolving disc normally rotates at a speed of 1 500 or 1 800 rpm, and the large bars near the center of the rotating disc set the chips to move with the disc. The grooved pattern on the discs tears the chips apart into smaller fragments and fibers. The pattern and the gap between the discs become narrower as the chips move towards the edges of the discs. By adjusting the gap between the discs, the desired fineness level of the pulp is achieved. [35] [36]

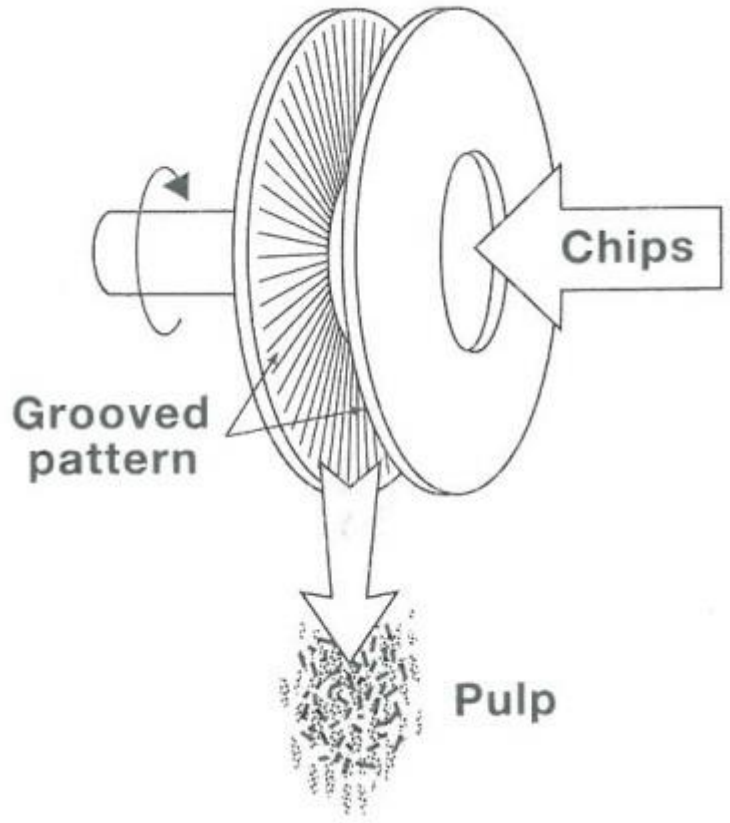

Figure 17. The disc blades of a RMP-defibrator. [36]

The defibrating process can generally be divided into two steps: defibration of chips and fibrillation of fibers. The wood chips are almost completely broken down before leaving the inner segment of the refiner blades, also called the breaker bar zone. The opposing bar pattern on the outer segment, or the refining zone, separates further the pulp and fiber bundles apart. The pattern on a certain disc blade is shown in Figure 18. [37]

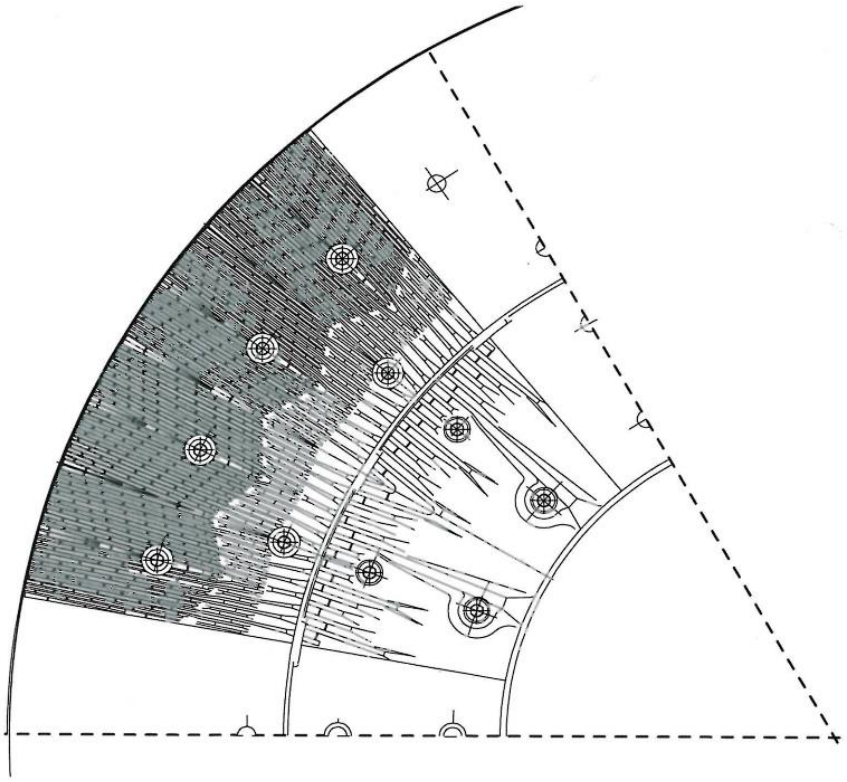

Figure 18. The pattern segments on a refiner's disc blade. [35]

In papermaking, it is desirable to separate the fibers as undamaged as possible. At low temperatures the lignin is stiff and the fractures generated during refining occurs in a more uncontrollable manner. Thus, the wood can be heated up to soften the lignin, or chemicals may be added to dissolve the lignin, and more intact fibers are received. Also the rotation speed of the discs affects the quality of the pulp. By increasing the speed, the refining becomes harsher. The characteristics of harsh pulping include a lower energy consumption, lower dry-content of pulp, and a shorter residence time of pulp in the refiner than in gentle refining. But then, the pulp from gentle refining is better fibrillated and the fibers are longer. [35] Because the purpose of the defibration in the DustComb is to disintegrate the wood without any requirements about the fiber quality, no heating of the wood is needed and the defibrating may be very harsh.

In mechanical pulping almost all of the wood is gained as yield and used as pulp, while in chemical pulping only the cellulose and hemicellulose is recovered, resulting in a yield of only about 50%. The yields from different pulping processes are presented in Table 12.

The specific energy consumption (SEC) of the refining is the ratio between energy consumption and pulp production. The SEC depends on the clearance between the discs, and hence the desired freeness of the pulp. For example, tissue and toweling (lightly refined paper using low yield, bleached pulp) require about 100-120 kWh/t pulp. [38] The other extreme is the mechanical pulping for top-quality magazine papers, which may require up to 3 500 kWh/t of electric energy. Also, great differences exist between the specific energy consumptions of various defibrator types. [34] [35]

Table 12. Comparison between the pulp yields from different pulping processes. [37]

Classification	Process	Yield (%)
Mechanical	Stone-groundwood	95+
	Refiner mechanical pulp	90+
	Thermomechanical pulp	90-95
	Chemithermomechanical pulp	80-90
Chemimechanical	High yield sulfite pulp	65-80
	Neutral sulfite semi-chemical pulp	65-80
	Chemimechanical pulp	70-80
Chemical	Kraft	40-50+
	Sulphite	45-55+

4.3 Drying of the pulp

Drying is an essential part of the biomass handling process, because biomaterials collected in the forests typically have water content around 50% (w.b). This high proportion has a significant effect on the quality of the biomass combustion or gasification. Drying is also needed in the production of solid biofuels, such as powders, pellets, and briquettes. The maximum moisture content required in these is normally between 10 and 20% (w.b). [18]

Various types of dryers are used in industrial facilities. The drying can either be direct or indirect, depending on how the heat for the drying is transferred to the moist material. In direct drying, the heat is transmitted by convection from drying gas. These types of dryers are the mostly used varieties, and for example flash- and fluidized bed dryers usually operate directly. In indirect dryers, the heat is transmitted to the material through a wall, i.e. the heat transfer is based on conduction. The cylinder drying used in papermaking is a typical indirect drying method. Additionally, the drying can in some cases be based on radiation, as in infrared drying. [20]

When drying biomass, the drying rate in direct drying is affected by following parameters: particle size and shape, particle properties (e.g. heat conductivity, effective diffusivity, permeability), and drying gas temperature. Also the heat losses to the environment and the humidity in the drying gas have decreasing effects on the drying efficiency. The heat and mass transfer rates in the particles increase with increasing temperatures, and faster drying is thus achieved with elevated drying and particle temperatures. The drying rate decreases with increasing particle size, because the required time to remove a given amount of moisture from a particle increases as the square of the particle diameter. [20] [39]

The DustComb-system is planned to be equipped with a flash dryer, but the drying tests in this work, which are presented and discussed in Chapter 5, were carried out with a fluidized bed dryer. Hence, these both types of dryers are presented and their functions are described in this chapter. These dryers are also compared with other types of dryers used in industrial applications and the effects of drying wood fuels are briefly analyzed.

4.3.1 Fluidized bed drying

Fluidized bed (or fluid bed) dryers are commonly used in the field of bioenergy and biofuels. In fluid bed dryers (FBD) the material to be dried forms a bed in the dryer. The drying medium is blown from below, making the bed float. The velocity of the drying medium has to be above the minimum fluidization velocity, but not too high to prevent the bed from leaving the dryer. A typical FBD system consists of a gas blower, gas heater, fluidized bed column, and gas-cleaning systems. The principle and components of a typical continuous fluidized bed dryer are illustrated in Figure 19. [39]

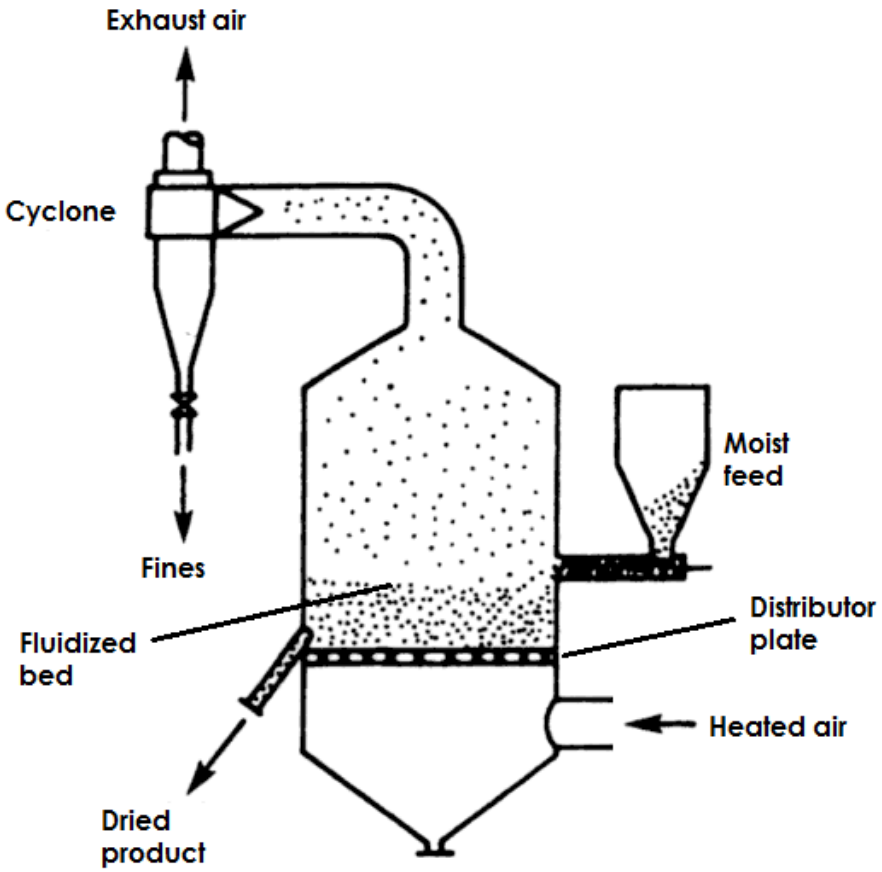

Figure 19. The principle of a continuous fluidized bed dryer. [40]

Good particle mixing is characteristic for fluidized bed drying. The mixing effect is generally good for particle sizes between 50 and 2 000 µm, but the size distribution should be relatively narrow. Flue gas is often used as drying medium when integrated with combustion, but also heated air and superheated steam are used. Steam is common in larger facilities with existing steam system. If steam is used as drying medium, it can be reheated and recycled. The excess steam evaporated from the biomass can be used as process steam elsewhere. Additionally, because the steam circulation is a closed process, no gaseous emissions are released to the atmosphere. On the other hand, the harmful compounds are gathered in the steam and proper steam cleaning equipment is required. [17] [39]

4.3.2 Flash drying

Flash drying is one of the most widely used drying systems, and it is also known as pneumatic drying. The flash dryers are continuous convective dryers, where the wet material is fed into a hot gas stream. Hot air is common as drying medium, but super-heated steam can also be used. When drying with steam instead of air, higher efficiency and product quality can be achieved. The gas stream transports the solid particles through the system and carries the heat required for the drying. [41]

A simple flash drying system includes a gas heater, wet material feeder, drying duct, particle separator, exhaust fan, and dried product collector. These parts are presented in Figure 20. The drying medium flows upwards the drying tube with a velocity significantly higher than the minimum fluidization velocity of the wet material. Continuous convective heat and mass transfer processes take place in the tube. [41]

Cyclone dust separators, fabric filters and electrostatic precipitators are used to separate the dried material from the drying medium at the end of the drying system. Further, wet scrubbers can be used to clean the exhaust air from pollutants. The flash drying systems usually consist of several drying towers in series. Between each drying column the moist air is separated from the particle flow. An industrial flash dryer for pulp drying is shown in Figure 21. [41]

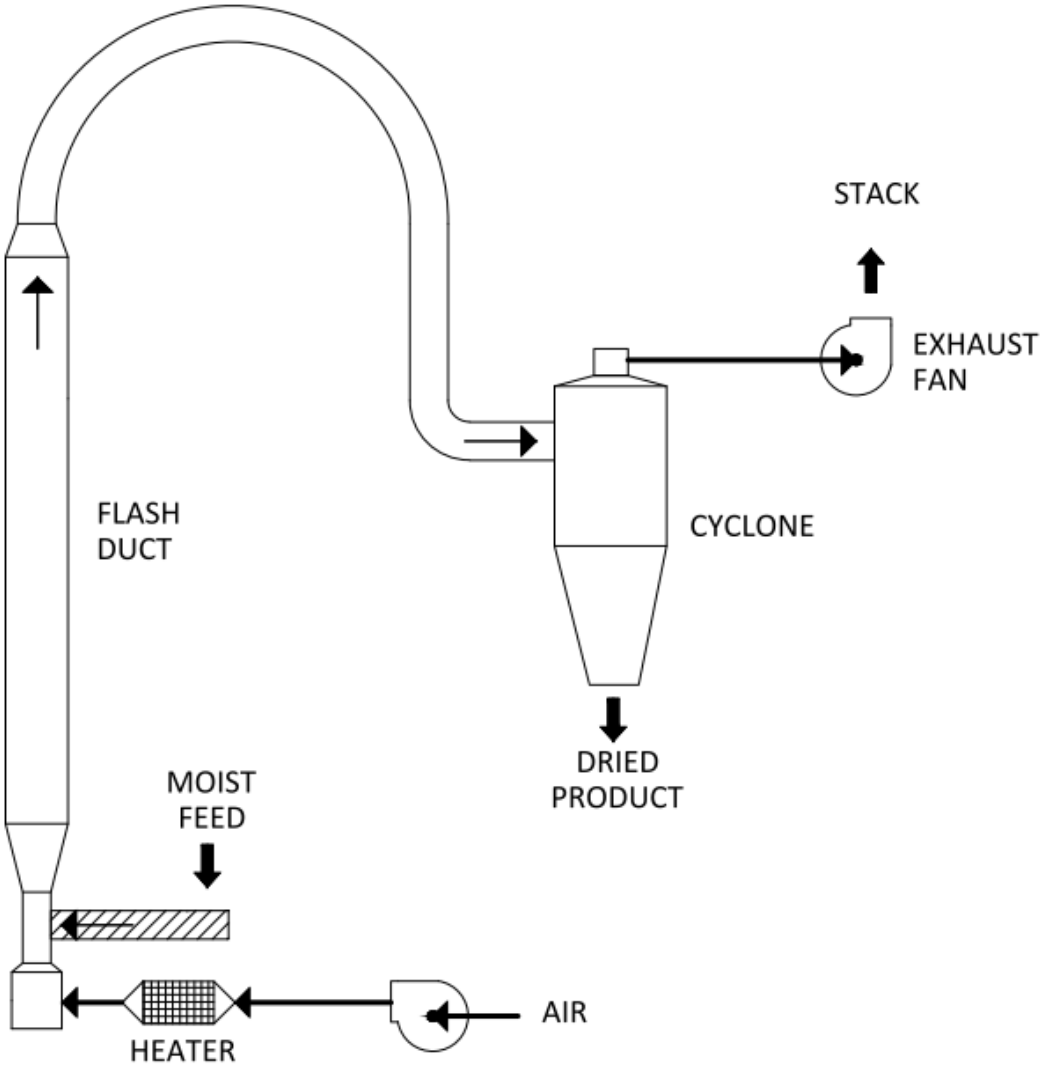

Figure 20. The components in a simple flash drying system.

Figure 21. A large-scale flash dryer for pulp drying. [42]

The size of particles to be dried in a flash dryer are normally restricted to the range of 10-500 µm. Typical features for flash dryers are the relatively short residence time (0.5-10 s) and high rate of evaporation. Due to the short residence time, flash dryers are sometimes used to remove only surface moisture and less of the internal moisture. In such cases, the temperature of the feed material stays low. The specific energy consumption level of flash dryers normally ranges from 4 500 to 9 000 kJ/kg of water evaporated. Better results can though often be obtained by optimizing operating condition and using more advanced technology. [41]

Some variants of flash dryers may be heated through the tube wall to keep up the temperature of the drying gas. For higher efficiency, the velocity and mass flow of the drying medium should be as low as necessary, but still high enough to achieve required materials transport and drying rate. The temperature of the gas should be as high as possible without exceeding limits imposed by the thermal sensitivity of the solids, safety considerations or dryer resistance. [41]

The main advantages with this type of dryers relate to the simplicity in construction: The capital costs are low, only a small land area is needed, and the operation is almost trouble free. The relatively small number of moving parts simplifies the maintenance, but the high attrition in the drying tube can increase the maintenance costs. This depends though on the construction materials in the dryer and also on the contents in the

material to be dried. Also the operation costs can be high if the specific energy consumption of the dryer is high. The high temperatures in the dryer increase the risk of fire and explosion. Another major disadvantage with flash dryers is the difficulty to dry material with easily clustering particles, because agglomerations need significantly greater fluidization velocities than separate particles. [41]

4.3.3 Comparison of dryers

Fluidized bed dryers have replaced some of the conventional dryers, such as rotary and conveyor dryers in many instances. Some characteristics of different dryers for solid particles are compared in Table 13. The advantages with flash and fluidized bed dryers compared to other types are the high rate of moisture removal, high heat and mass transfer rate, high thermal efficiency, ease of control, and low maintenance costs. [39] [41]

The drying gas velocity has a dominant effect on removing surface moisture from particles. Higher drying rates are achieved by increasing the gas velocity. Flash dryers are thus the most suitable dryers for small particles. On the other hand, the requirements for the particle size distribution in flash dryers are strict and the fuel has to be homogenous to ensure good quality of the drying. Also the high erosion of pipes and agglomeration of the particles are common disadvantages in both flash and fluid bed dryers. A common problem in all types of dryers is the corrosion and erosion caused by the acidic and corrosive condensate. This has to be taken into account when designing dryers. [39] [41]

Table 13. Comparison of the typical properties of different dryer types. [39]

Criterion	*Rotary*	*Flash*	*Conveyor*	*Conventional FBDs*	*Modified FBDs*
Particle size	Large range	Fine particles	500 µm - 10 mm	100 - 2 000 µm	10 µm - 10 mm
Particle size distribution	Flexible	Limited size distribution	Flexible	Limited size distribution	Wide distribution
Drying time (approx.)	Up to 60 min	10-30 s	Up to 120 min	Up to 60 min	Up to 60 min
Floor area	Large	Large length	Large	Small	Small
Turndown ratio	Large	Small	Small	Small	Small
Attrition	High	High	Low	High	High
Power consumption	High	Low	Low	Medium	Medium
Maintenance	High	Medium	Medium	Medium	Medium
Energy efficiency	Medium	Medium	High	High	High
Ease of control	Low	Medium	High	High	High
Capacity	High	Medium	Medium	Medium	High

4.3.4 Effects of drying

The emission of nitrogen oxides is strongly dependent on the flame temperature. Thus, when burning dry fuel, the amount of NO_x emitted generally increases as the combustion temperature increases. When drying the biomass, volatile organic compounds such as terpenes, carbolic acids, and light aldehydes and alcohols, are vaporized. These compounds are known to form ground level ozone in the presence of nitrogen oxides, and are thus of environmental concern. On the other hand, when burning very moist fuel, the low temperature causes increased amounts of unburned hydrocarbons in the flue gases. The unburned fuel decreases the efficiency of the combustion, which leads to higher fuel consumption and increased emissions. [17]

The thermal breakdown of wood materials and release of VOCs comes into action at the temperature of about 150°C. The hemicelluloses start to degrade and alcohols, acids and aldehydes are released. The rate of degradation depends strongly on the temperature and it is increased rapidly with increasing drying temperature. The degradation involves energy losses to the overall process. Alternatively, if the VOCs are recovered, they can be combusted and used as a heat source. [17]

To avoid the release of VOCs, the temperature of the feed material should be maintained low (<100°C) and the final moisture content should remain as high as possible. It is possible to dry wood fuels to about 10% (w.b) without emitting a harmful amount of organic compounds. This can be achieved in a bed dryer when the inlet drying gas temperature is max 180°C and the steam formed is not condensed. The released steam prevents the material from over-drying as long as part of the bed material is still moist. Also, a wide range of particle size distribution may increase the VOC-emissions, as the smaller particles tend to over-dry. [16] [17]

If the drying is carried out in high temperatures and the oxygen concentration in the drying medium is over 10 vol.-%, the risk of fire or explosion during the drying is increased. High temperatures should thus be avoided unless a low-oxygen environment is guaranteed. There is also a risk of spontaneous ignition in the thermally dried fuels during handling and storing. Proper cooling after drying reduces the risk of self-ignition. [17]

5 Experimental study

To evaluate the profitability of the DustComb-process both from an economic and ecologic point of view, the specific energy consumptions of the refining and drying need to be found out and compared with the amount of available energy recovered from the combustion of the wood fines. The aims with the experimental part of this work are to assess how the specific energy consumption of the refining depends on the disc clearance in the defibrator, and to find out how much the particle sizes of the fines affect the drying rate. The produced material is also visually analyzed to find out if it is applicable as a fuel in pulverized fuel firing, and if the mechanical defibrator is suitable for producing the fuel.

In this chapter the experimental arrangements are described, the results of the tests are presented, and the results are discussed. The results received in this chapter are further used in the calculations in Chapter 6, where the profitability of the DustComb-process for commercial use is evaluated.

5.1 The feedstock

Wood chips from fresh birch (Figure 22) were used as raw material in the tests. Birch was chosen due to its better properties as a fuel than softwoods, which was described earlier in this work. To achieve as homogenous results as possible, chips from only one species were used. Randomly chosen samples from the raw wood chips were collected and the moisture contents of the samples were measured. The average moisture content of the samples in the feedstock was calculated, resulting in 45% (w.b).

Figure 22. Wood chips from fresh birch.

5.2 Moisture analyzing

To measure the moisture content of the samples accurately in this work, a thermogravimetric analyzer was used. The device was a Precisa XM 60 moisture analyzer (Figure 23). A sample was put into the analyzer, which heated up and dried the moist matter with a halogen lamp while constantly weighing the sample. The temperature inside the analyzer was kept constant at 105°C. The analyzer drew a drying curve where the mass of the sample was presented as function of time. The drying curves of a set of samples are presented in Figure 24. The measuring was stopped when the mass change rate decreased below the set parameter. The parameters for the measurements of each type of samples are presented in Table 14.

The moisture content was measured from the wood chips before defibering and from the defibrated wood both before and after drying. A set of 3-5 specimens were taken from each sample lot, and the moisture content in each specimen was measured with the analyzer. The moisture content in each sample lot was defined from the average value of the moisture contents in the specimens.

Figure 23. Precisa XM 60-thermogravimetric analyzer.

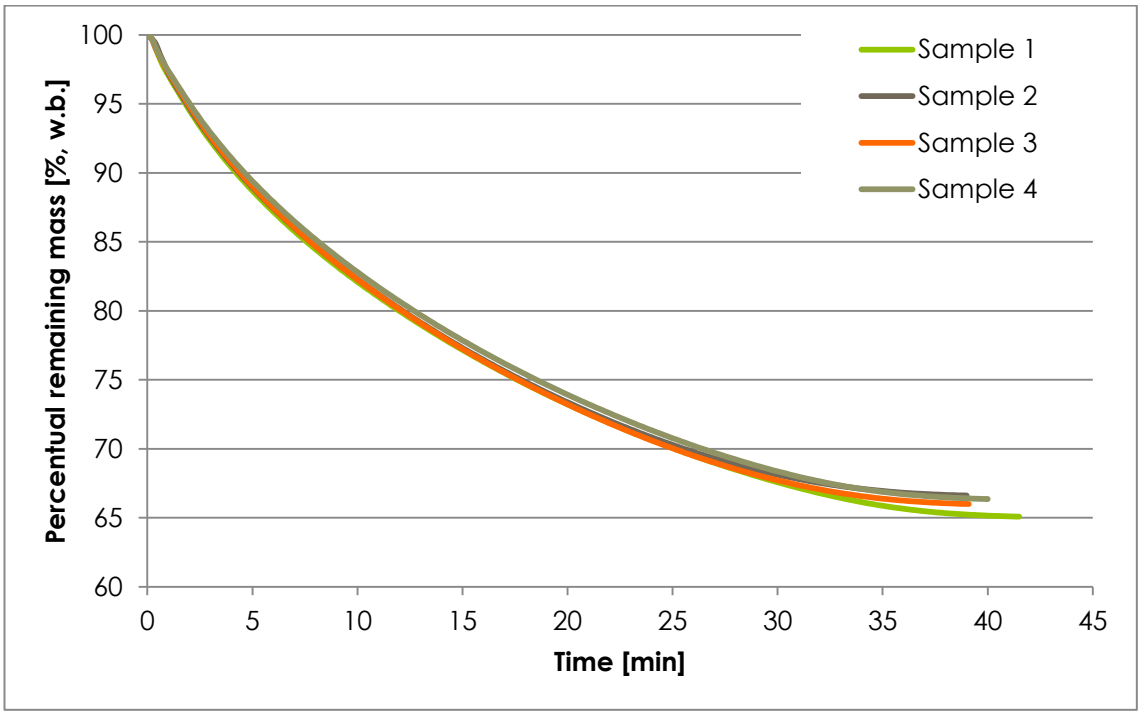

Figure 24. The moisture analyzer's drying curves for a 1.00 mm set of samples before drying. The remaining mass of the sample is given as proportion of the initial mass.

Table 14. Parameters for the moisture content measurements. The analyzer stopped the measurement when the mass change rate decreased below the measurement stop parameter.

Sample type	*Unit*	*Wood chips*	*Fines before drying*	*Fines after drying*
Sample size	g	20 ± 0.2	9 ± 0.02	5 ± 0.02
Measurement stop	Δmg/s	1/20	1/30	1/60

5.3 Defibration

A laboratory defibrator was used to produce the refined fuel and to measure the energy consumption of the defibration. The gap between the refining discs was adjusted to measure how the SEC is affected by the varying disc clearance, and to produce samples with different particle sizes.

As mentioned earlier in this work, the SEC describes the energy consumption of the refining process. It is the ratio between the amount of consumed energy and the amount of produced pulp. The gap between the defibrating disc blades controls the energy consumption and freeness of the fines. [35]

5.3.1 Test procedure

The defibration tests were carried out with a Sprout-Waldron 105-A single-disc defibrator (Figure 25). The defibrator was equipped with a vibratory feeder, which fed wood chips to a screw feeder. The screw feeder carried the chips further into the defibrator. The defibering discs (model C2976) were made from acid resistant steel (Ni-hard) and their diameter was 300 mm. The opened defibrator and the disc blades are represented in Figure 26. The feeding screw was attached to the static front disc, and the rotating disc was mounted into the shaft run by an electric motor. The disc clearance was changed by adjusting the location of the axle linearly. The different components of the defibrator are illustrated in Figure 27.

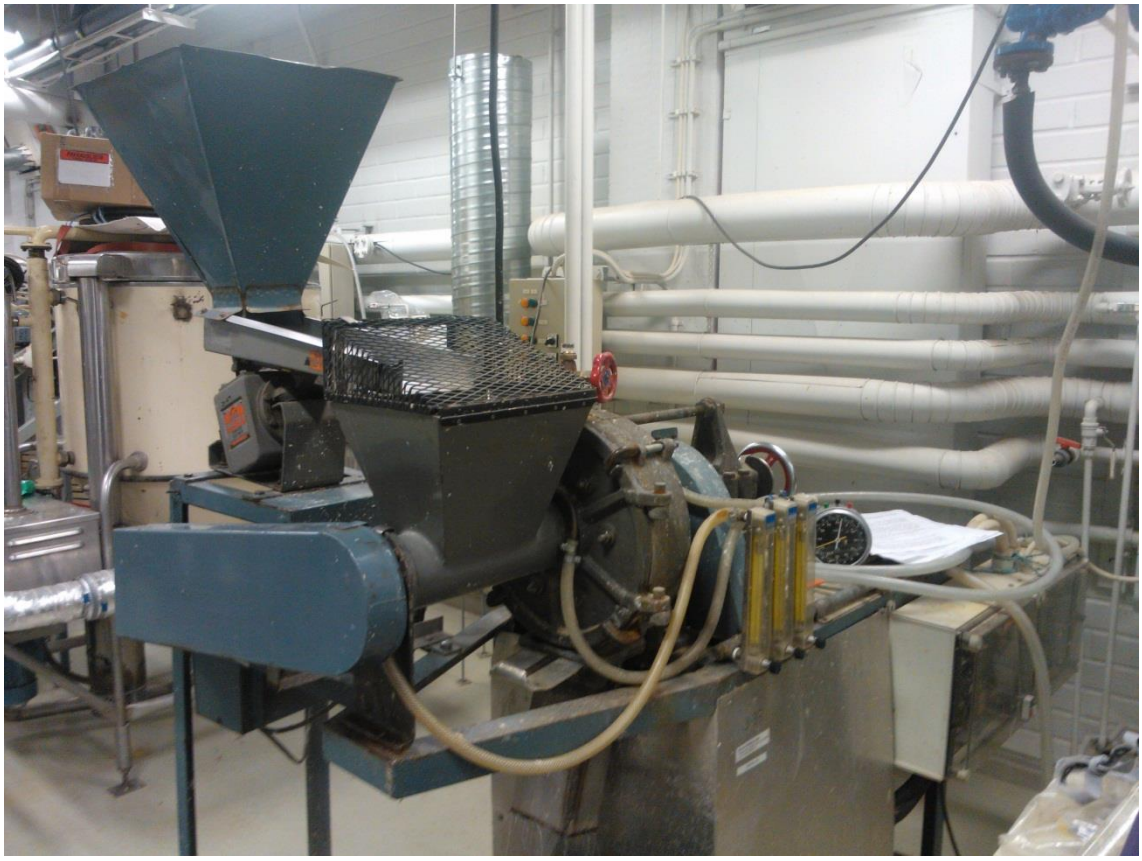

Figure 25. Sprout-Waldron 105-A laboratory-defibrator.

The electric motor rotated with a constant speed of 1 500 rpm and its nominal power was 45 kW. By the use of belt transmission, the shaft and the rotating disc were set to rotate at a speed of 3 000 rpm. The total energy consumption of the refiner was measured by an energy meter with an impulse counter connected to the motor. The energy consumption calculations are presented in the next chapter.

The defibrator was equipped with three water inlet nozzles. In normal pulping, water is fed into the defibrator to dilute the pulp with water. The water also lubricates the blades and keeps the temperature low in the refining zone. [35] In this work, the wood was defibrated without water to minimize the drying needs of the produced pulp. Feed water was only used to flush the refiner between the tests.

Because no running water was used, but due to the moist in the wood, part of the pulp caked together and stuck inside the refiner. In order that the stuck material would not

distort the SEC-measurements, the SEC was calculated on the basis of the input mass instead of the gained pulp's mass. Each sample was weighed before feeding it into the defibrator. The sample sizes generally ranged between 400 and 1 000 g on wet basis.

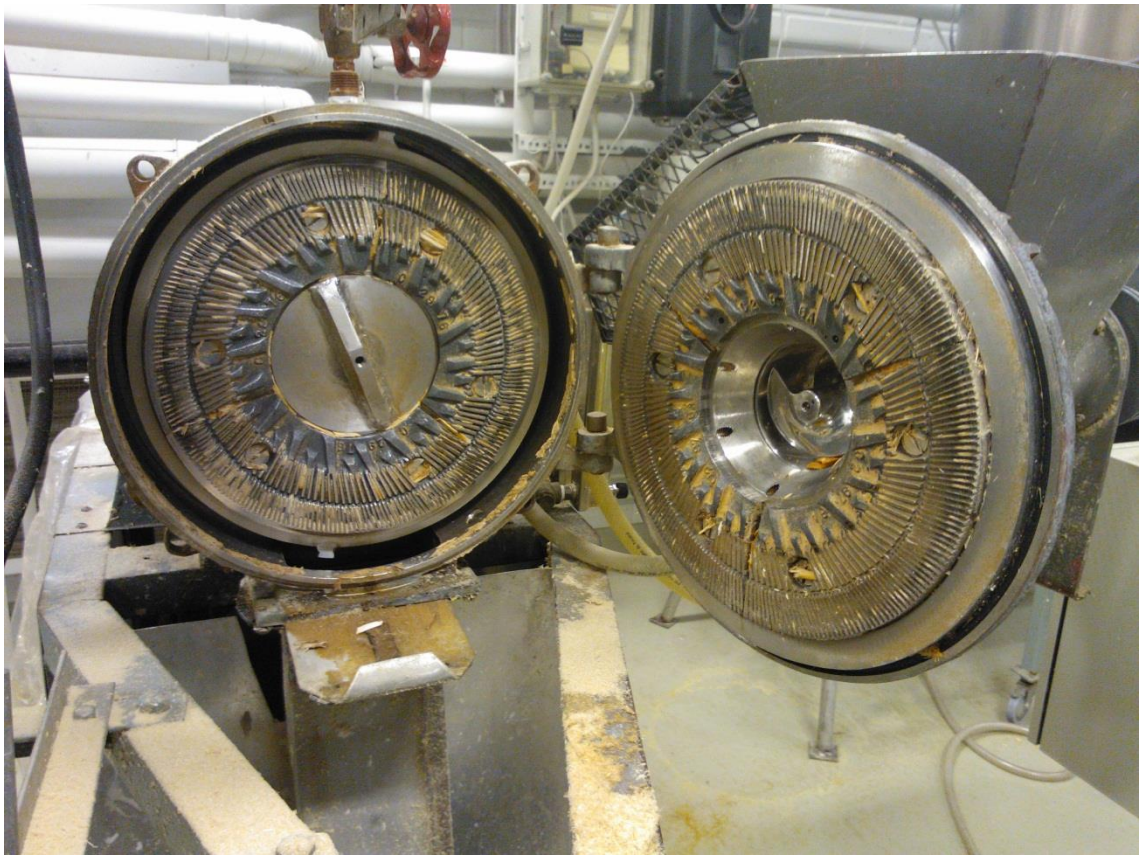

Figure 26. Defibrator disc blades. The rotating disc is on the left and the stationary front disc with the screw feeder is on the right.

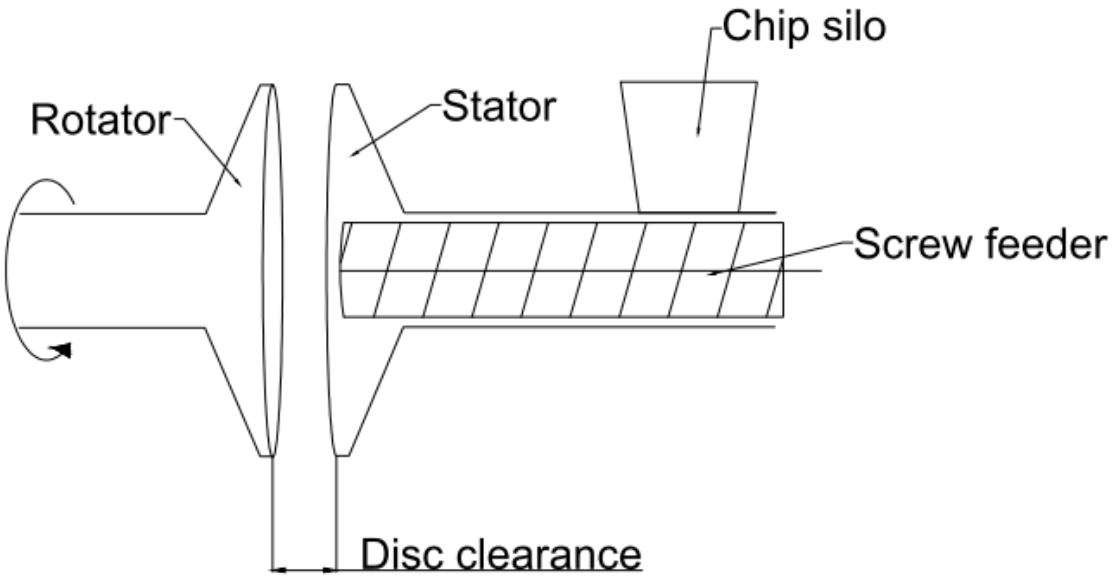

Figure 27. The principle of the test defibrator and the chip feeding system.

The disc clearance is normally measured as the gap between the plates at the outer periphery of the plates. [34] The specific energy consumption of the defibration was measured with disc clearances between 0.60 and 1.80 mm. Wood fines produced by defibrating with 0.80 mm disc clearance are presented in Figure 28. The figure shows that the refining yields fines of a wide size distribution. To produce pulp for papermaking, the disc clearance is normally narrower than 0.8 mm. In [43], Eskelinen mentions a critical disc clearance ranging from 0.2 to 0.3 mm, below which the fibers are cut severly and chunky fine material is generated resulting in lower strength properties of the pulp.

Figure 28. Size of the material gained from dry refining with 0,80 mm clearance.

The feeding rate of the wood chips was adjusted according to the defibrator's capacity to work properly with different disc clearances. The residence time of the material between the discs varied depending on the disc clearance. With narrow clearances (< 0.80 mm), the feeding speed had to be kept very low. More about the feed rate in the refining experiments is discussed in Chapter 5.3.3.

A too high feed rate led to overheating and smoke formation from the wood, especially with disc clearances of 0.80 mm and below. This phenomenon was characteristic for the tests in this work because no water was fed to cool down, transport heat away and to lubricate in the defibering process.

The output material was collected into a bucket and each sample was stored separately in air-sealed plastic bags. The moisture content of the wood after refining was measured from a few samples to calculate the average reduction of the moisture content during the refining. The samples were frozen between refining and further processing to prevent

any decomposition in the wood. The samples were classified according to the disc clearance used in each defibration test. From now on in this work, the different particles size classes are defined by the disc clearance used in each defibration test.

5.3.2 Calculation of the specific energy consumption

The energy consumption of the defibration is calculated from the amount of electric pulses sent to the refiner's motor during a period of time. One pulse was set equivalent to 10 Wh. When measuring the SEC, the defibrator's idling power has to be determined and subtracted from the measured total energy consumption of the process. Hence, the feeding rate has no effect on the SEC.

To ensure that the different disc clearances were not affecting the idle energy consumption, the idling power was determined for each used disc clearance several times between the defibering tests. The idling power was measured by running the defibrator without feeding any chips into it during a specific period of time (in these tests generally 160 to 280 seconds), and counting the amount of electric pulses sent to the motor. The power is calculated by using the following equation:

$$P_{idle} = a \cdot 10\ Wh \cdot \frac{3600\ s/h}{\Delta t}, \tag{5}$$

where P_{idle} is the idling power [W], a is the mount of electric pulses, and Δt is the length of the time period [s].

The specific energy consumption of the refining of a sample is calculated from the input sample size, refining duration, and amount of electric pulses sent to the motor, by using Equation (6). The dry mass of the samples is calculated by defining the absolute mass of water in the sample from the average moisture content in the wood chips, and by subtracting it from the total sample weight.

$$SEC\ \left[\frac{MJ}{kg}\right] = \frac{a \cdot 10\ Wh \cdot 3600\ \frac{s}{h} - P_{idle} \cdot t}{m_{dry}}, \tag{6}$$

where a is the amount of electric pulses, t is the duration of the defibration [s], and m_{dry} is the dry mass of the input sample lot [kg].

5.3.3 Defibration results

The measured idling power values are presented in Figure 29. No regular changes in the idling power are observed in the figure when the disc clearance is changed. The average idling power of the defibrator is determined to 3.0 kW on the basis of the measurements.

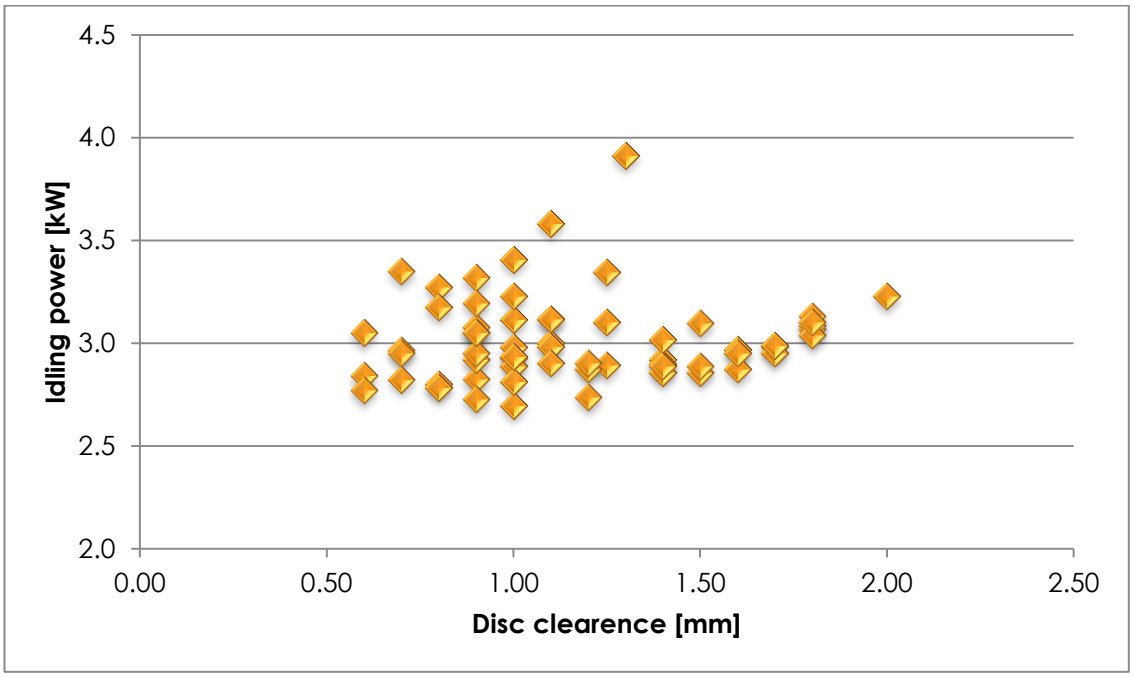

Figure 29. The dependence between idle energy consumption of the defibrator and the clearance between the discs.

The average defibration SEC-values for each disc clearance are presented in Figure 30. The figure shows how the specific energy consumption of the defibration increases with narrowing disc clearance. A considerable increase in the SEC can be noticed in the graph when the disc clearance decreases from 1.0 mm to smaller. The measured average SEC of the refining in this work varied from under 600 kWh/t, with disc clearances over 1.10 mm, up to nearly the double when the disc clearance was narrowed to 0.60 mm. There is no significant change in the energy consumption when widening the gap from 1.20 mm.

Typical energy consumption levels of 4.5-11 MJ/kg (1 250-3 060 kWh/t) in mechanical pulping for papermaking are mentioned in the literature. [43] These values fit into the plot in Figure 30 for narrower disc clearances than 0.60 mm.

The measured SEC is much dependent on the type and size of the refiner, and the type and condition of the disc blades. Thus, with newer large-scale defibrators it may be possible to reach specific energy consumption levels as low as 50 kWh/t, and still resulting in an outcome material of the same size as the fines from 1.0-1.5 mm disc clearance in this work. [44] In the calculations in Chapter 6, the refining SEC of 600 kWh/t will be used. A reference value of 100 kWh/t will be used as an assumed SEC for the process.

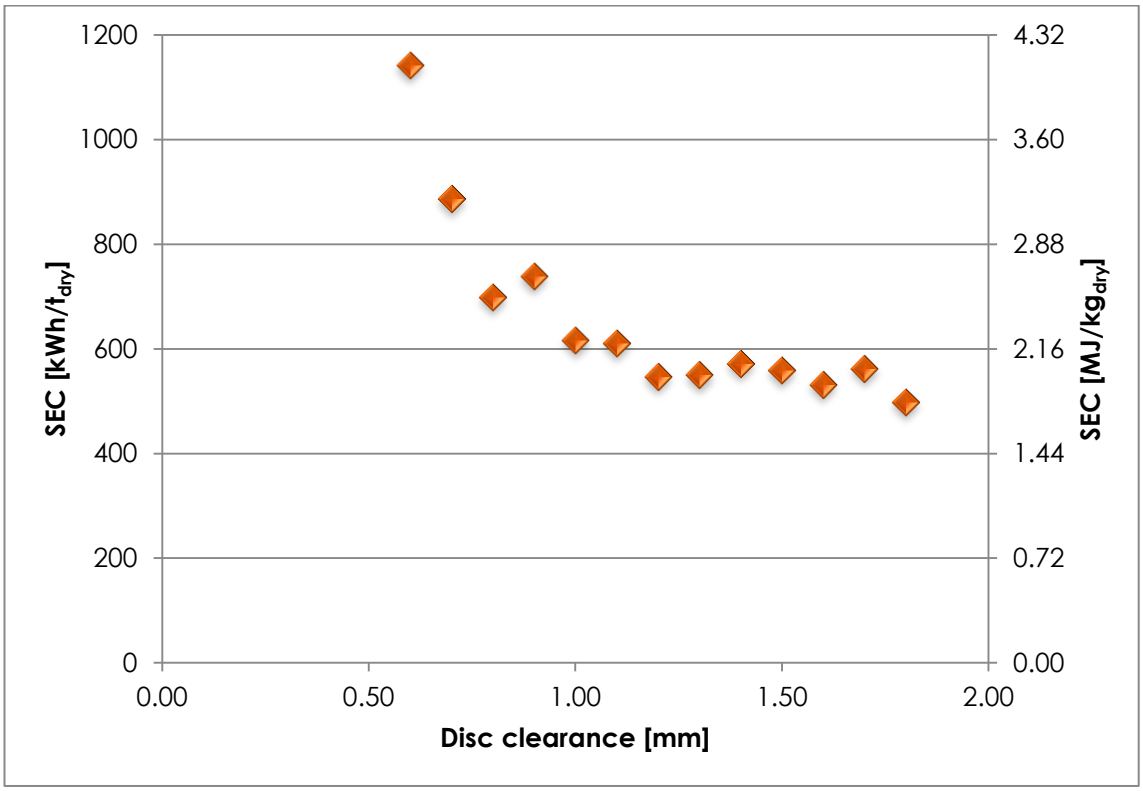

Figure 30. Average values of the specific energy consumption with different disc clearances.

The average feeding rate of each defibering sample is calculated based on the input sample size and refining duration. The results are presented in Figure 31. A significant reduction in the capacity of the defibrator can be seen in the graph when the gap between the discs is narrowed. With the defibrator used in the tests, the average feed rate declined from 2.4 g/s to almost 0.5 g/s when reducing the disc clearance from 1.80 mm to 0.60 mm. This capacity decrease has no effect on the defibration SEC. However, the total energy consumption of the defibration increases with lower feeding rates, because the idling energy consumption is dependent on the duration of the defibration. Also the investment costs may increase if the capacity has to be increased due to the low feed rate.

Due to the heat generated inside the defibrator, the wood dries during the defibration when no additional water is fed. The measured moisture contents in each sample between refining and drying are presented in Figure 32. During the defibration, the material is dried substantially from the initial moisture content of 45% in the raw wood chips. About 16-25% of the water is removed in the defibration process, resulting in end moisture contents ranging from 34% to 38% (w.b). However, no clear dependence between the end moisture contents and disc clearances is observed in the results.

Because the refined wood was still warm and packed tightly directly after defibering, a significant amount of drying potential and generated heat remained unutilized. Thus, further research is needed including investigating how much the material is moreover dried if it is carried with air some distance directly from the refiner's outcome. In the DustComb-concept the refined material is planned to be blown straight from the defibrator to the dryer. The material temperature before the dryer should also be measured to evaluate if it is feasible to recover heat from the moist exhaust air, which is separated from the material flow before the dryer.

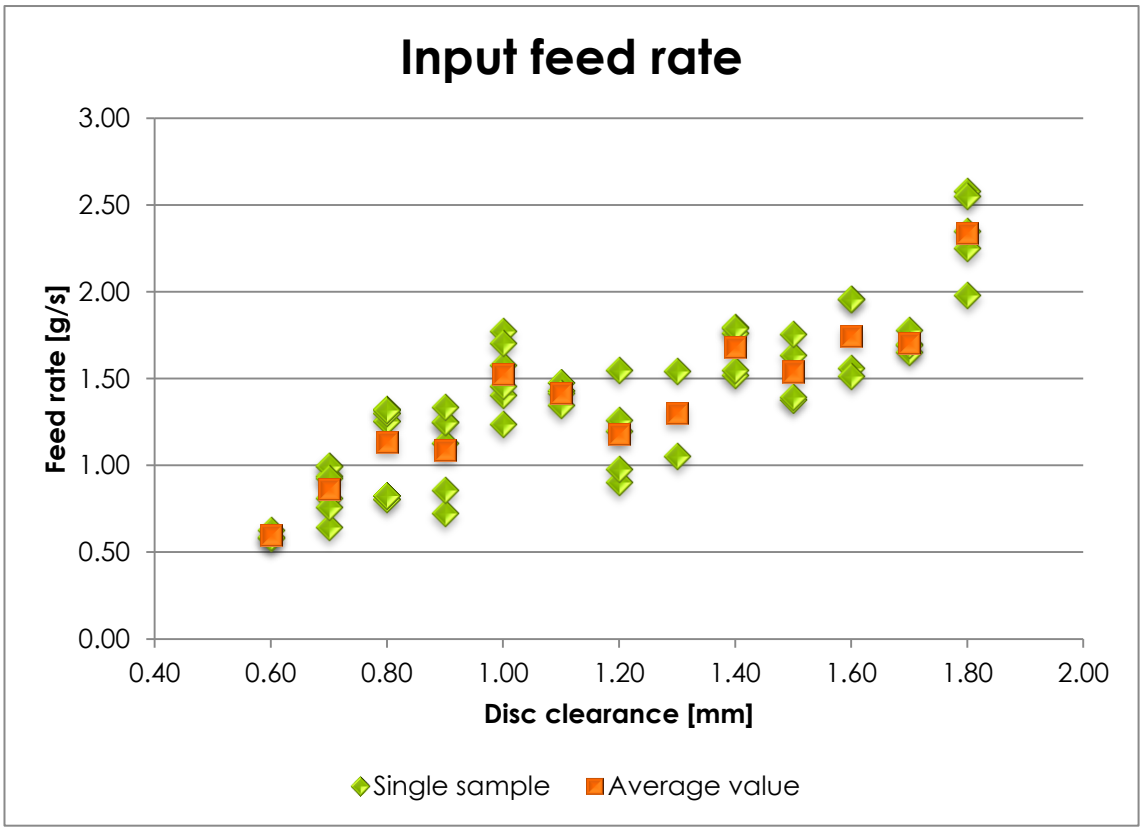

Figure 31. The calculated and average feed rates of the chips into the defibrator with different disc clearances.

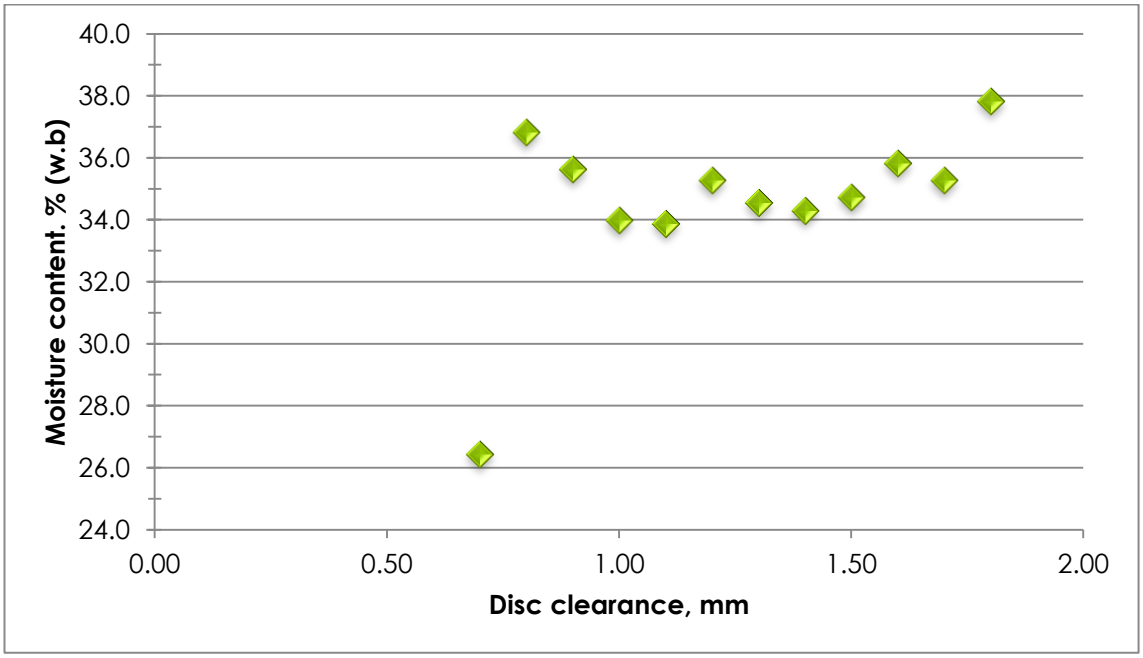

Figure 32. Moisture contents after defibration. The moisture content in the wood was 45% (w.b) before the defibration.

Furthermore, the theoretic amount of energy utilized when water is evaporated during the defibration, is calculated from the theoretic amount of heat needed to evaporate water. The chips were at room temperature when fed into the refiner, i.e. 20°C. Thus, by using Equation (3), the amount of heat needed to evaporate the water in the chips is calculated to 2 452.4 kJ/kg. The theoretic specific amount of heat needed to evaporate water in each sample lot is calculated based on the moisture reduction in the sample lot during the refining. The relative shares of input energy consumed by evaporating water are presented in Table 15 and illustrated in Figure 33.

The share of energy consumed to water evaporation varies between 15 and 25%. Eskelinen [43] reports that a level of 75 to 85% of the total input energy is consumed in the generation of steam during the refining. This level is though measured for normal refining conditions, where additional water is fed. These values cannot thus be directly compared to each other. Additionally, a significant amount of the specific refining energy consumption goes to losses, such as heating of the defibrator.

Table 15. The theoretic amount of energy needed to evaporate water during the refining.

Moisture content prior to refining:	45.31 m-% (w.b.)
Heat of evaporation:	2.452 MJ/kg_{water}

Disc clearance	*Moisture content after refining*	*Refining SEC*	*Evaporated water*	*Heat needed for water evaporation*	***Share of the total SEC***
mm	*m-% (w.b.)*	*MJ/wet-kg $_{wood}$*	*kg $_{water}$ /kg $_{wood}$*	*MJ/kg $_{wood}$*	*%*
0.70	26.43	1.747	0.189	0.4629	**26.50**
0.80	36.83	1.375	0.085	0.2079	**15.12**
0.90	35.64	1.454	0.097	0.2371	**16.30**
1.00	33.99	1.214	0.113	0.2775	**22.87**
1.10	33.88	1.203	0.114	0.2802	**23.30**
1.20	35.28	1.077	0.100	0.2459	**22.84**
1.30	34.55	1.084	0.108	0.2638	**24.33**
1.40	34.30	1.126	0.110	0.2699	**23.96**
1.50	34.73	1.102	0.106	0.2594	**23.54**
1.60	35.82	1.047	0.095	0.2327	**22.23**
1.70	35.27	1.106	0.100	0.2461	**22.25**
1.80	37.83	0.981	0.075	0.1834	**18.68**

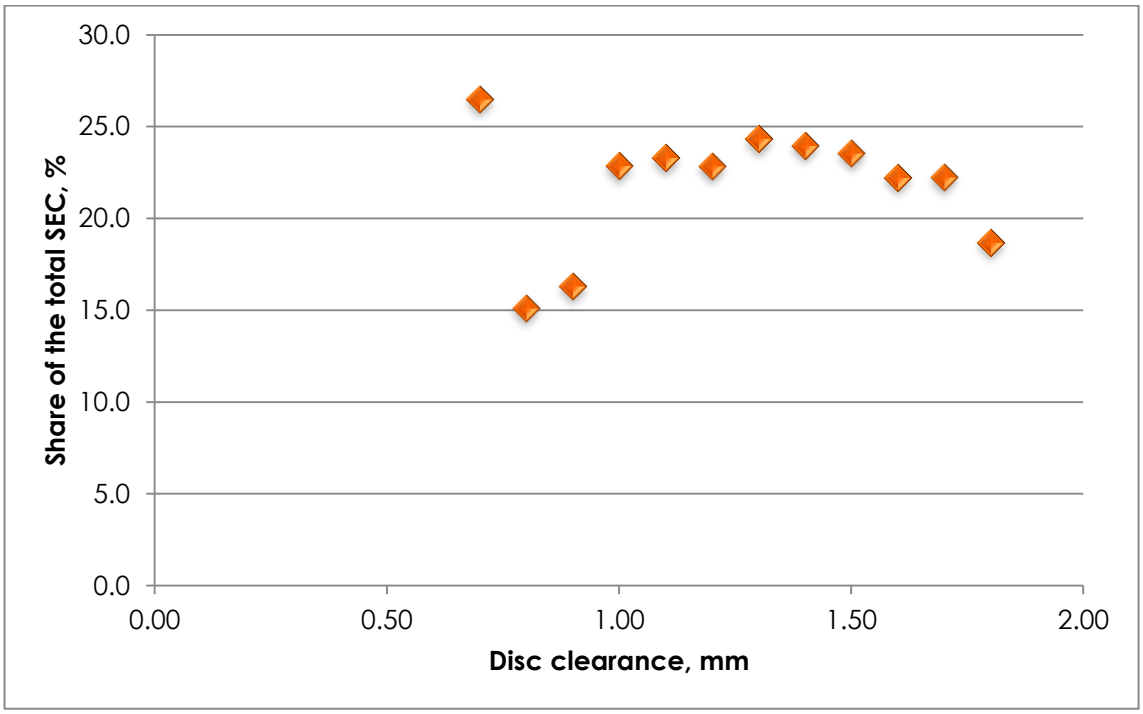

Figure 33. The share of the specific energy consumption needed to evaporate water during the refining.

5.4 Drying

The aim with the drying tests in this work is to observe how much the size of the particles affects the drying rate of the material. Also the fluidizing behavior of the material in the dryer is examined. The defibrated moist material samples were dried in a laboratory fluidized bed dryer, where the energy consumption and inlet air temperature were kept constant. The moisture reduction in the material and the durations of the drying tests were measured.

5.4.1 Test procedure

The drying tests were carried out with an Apex laboratory fluidized bed dryer (Figure 34). The main parts in the dryer were the plastic vessel, blower, heating resistors, and dust bag. The material to be dryed was put into the round vessel (Figure 35). The vessel's diameter was 380 mm, height 230 mm, and maximum capacity 8.5 litres. The bottom of the vessel consisted of a 200 mesh (hole size 74 µm) stainless steel net. A dust collecting bag was attached on the top of the vessel to prevent the bed material from leaving the vessel.

The drying air was blown through the bed from the bottom with a 0.7 kW blower located on the top of the dryer. The drying air was heated up with electric resistors. The drying in this work was performed with maximum heating power, i.e. 6 kW, to reach as close as possible the conditions in a flash dryer. The maximum nominal heating air

temperature in the dryer was 60°C. The real drying air temperature could however not be measured.

The ambient air temperature and humidity were measured before the tests, and the exhaust air and humidity were measured during the drying. It was not possible to measure the moisture content in the bed during the drying, so the approximate moisture level in the bed was found out from the output air humidity. The residence time was adjusted on the basis of the output air humidity to receive desired end moisture contents in each sample. The accurate moisture content for each sample was measured after the drying.

Figure 34. The laboratory fluidized bed dryer.

Figure 35. The bed material in the vessel of the fluidized bed dryer.

5.4.2 Drying results

Because absolute drying values comparable with flash dryers, such as specific energy consumptions, could not be produced, the results from the drying tests in this work are only compared with each other. To investigate if the particle size affects the drying rate, the average relative mass reduction rate is calculated for each sample. The results are presented in Figure 36. Because the drying rate falls as the material dries [20], the final moisture content of each sample is also presented in the same figure to clarify if the moisture content in the dried material was remained high.

Because no real-time values of the moisture content in the bed were possible to be measured with the available equipment, the samples could not be dried to the same final moisture. Due to the fact that the drying rate is not constant, or the drying rate decreases with decreasing moisture content, the calculated average drying rates of the different samples cannot be accurately compared with each other. However, samples dried to similar moisture levels are separated from Figure 36, and their average drying rates are represented in Figure 37.

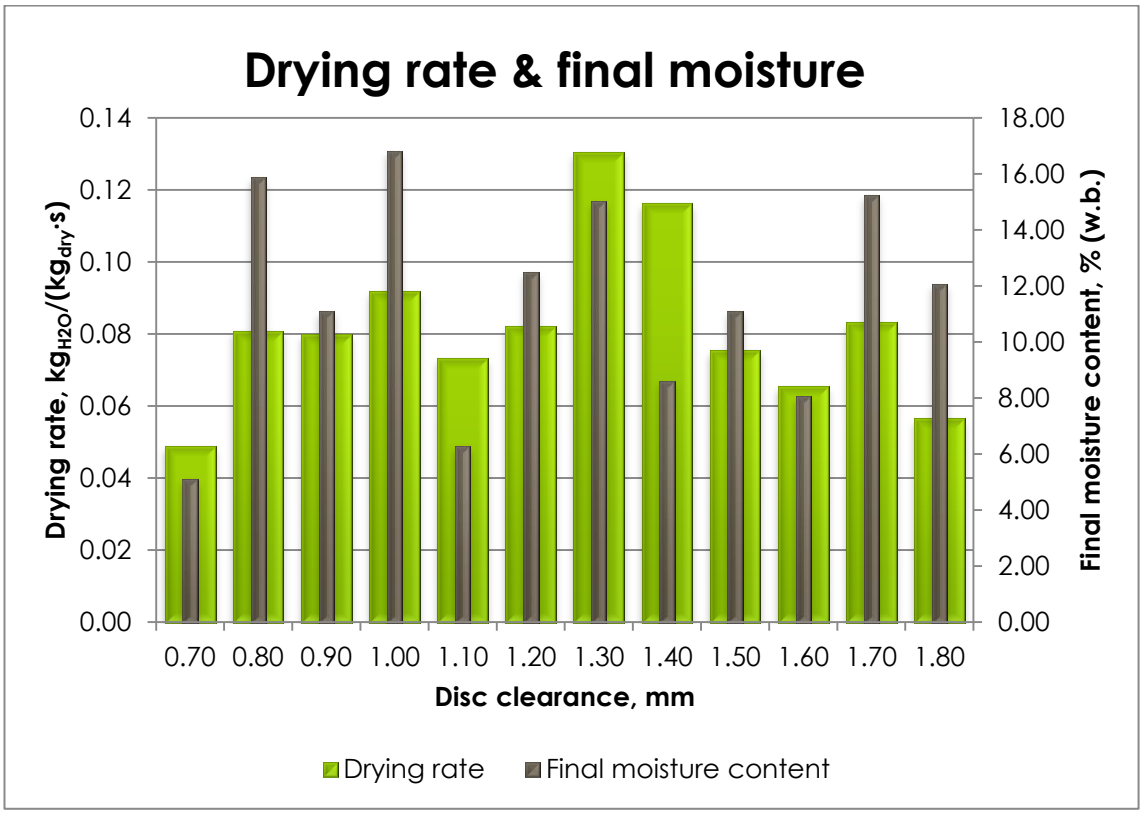

Figure 36. The average rate of mass decrease percentage and the final moisture content for the different particle sizes.

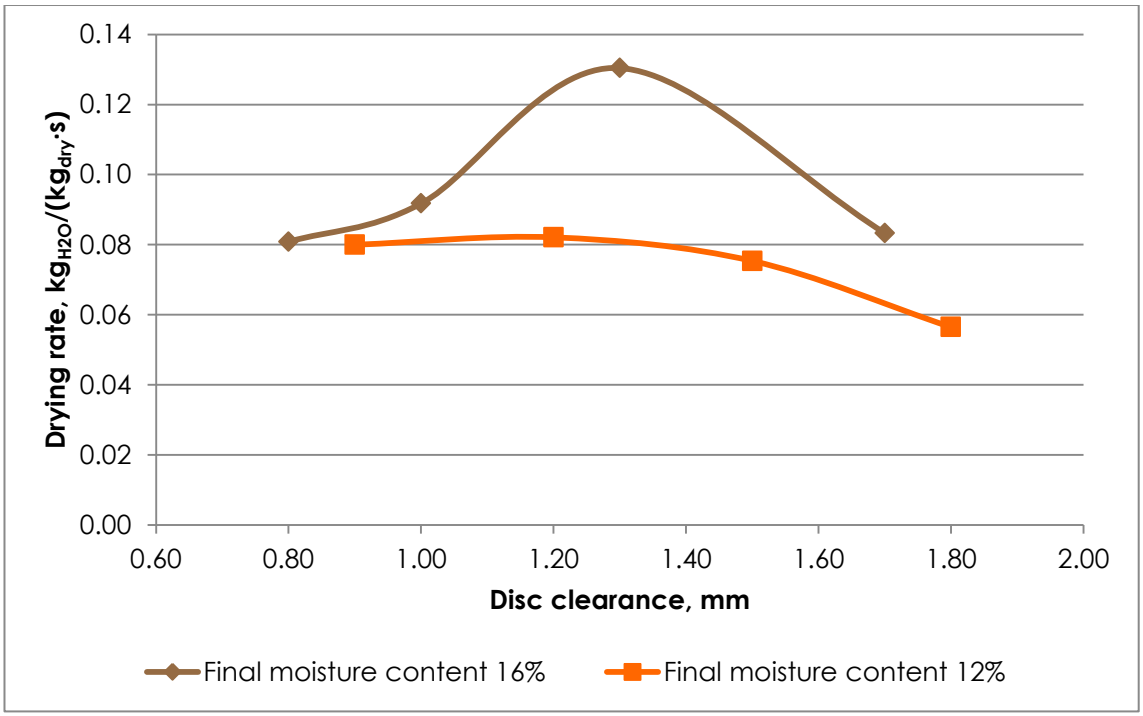

Figure 37. The average drying rates of samples with different particle sizes dried to a similar final moisture level. The change of average drying rates of two sample sets with similar final moisture is presented as a function of the material fineness.

In Figure 37, the upper curve represents the average drying rates for four samples dried to the final moisture level of 16% ±1 (w.b), and the lower represents the rates for four samples dried to the moisture level of 12% ±1 (w.b). The congruent characteristics with the both curves are that maximum drying rates are reached for the samples defibrated with 1.20 - 1.40 mm disc clearances. In the upper curve the average drying rates are at the same level for both small and large particle sizes, while in the lower curve the average drying of the large particle sizes is slightly slower than of the finer material. Hence, the trend of the lower curve is more in accordance with the fact that the specific moisture removal is faster for smaller particles because of the greater area to volume ratio. [20]

The wood fines in the drying tests could not be fluidized with the available equipment. A possible explanation can be found in research results by Zhong et.al. [45] Here, the behavior of long thin biomass particles in a fluidized bed was investigated. The minimum fluidization velocity turned out to increase with increasing length to diameter ratio of the biomass particles. In other words, long thin particles need higher drying medium velocity for fluidization than particles with more spherical shapes. This might be due to the phenomenon that long thin particles are usually bridging and enwinding each other. When the particle's length/diameter-ratio exceeds a certain value, they cannot be fluidized without any second fluidization medium, e.g. sand. [45] One explanation for this may also be the aerodynamic shape related to the mass of the particles: Longer fines have higher masses, but the air resistance is small.

Since the results from the drying tests are too inaccurate, no unambiguous conclusion can be drawn from the curves in Figure 37. Further research is needed to find out how substantial the effect of the particle size is on the drying rate of these wood fines in a flash dryer. This is essential for determining the optimal particle sizes for the Dust-Comb-process. The differences in drying rates also have an essential effect on the sizing of the dryer, especially with flash dryers where the residence times of the fines are very short. Further research related to the biomass particles in this work and their ability to fluidize is also needed. The minimum fluidization velocities and drying rates for samples with different particle sizes need to be analyzed further with more suitable equipment.

5.5 Density measurements

The density of the defibrated wood was measured and the results are presented in this chapter. The results will be used in the calculations in Chapter 6. The average density was measured with samples, where material with different fineness was mixed. The density was measured for the fines mixture without drying (moisture content 35%, w.b) and for mixtures dried to moisture contents of 15% and 0% (w.b).

The density tests were carried out by measuring the mass of material fit into a 0.5 dm^3 can. The defibrated material was compressed and allowed to expand by itself to its end volume before measuring the mass and volume. The idea with this proceeding was to simulate the situation where the fuel is packed without much effort.

Also, the average densities of fresh wood chips and wood pellets were measured. The results proved to be similar to the values in literature and they are represented in Table 16 together with the measured densities of the defibrated wood samples.

Table 16. Measured densities of wood fuels.

	Wood pellets	Wood chips	Defibrated wood		
Moisture content mass-% (w.b.)	8	45	35	15	0
Bulk density kg/m^3	600	300	140	110	100

5.6 Summary of experimental tests

The specific energy consumption of the refining starts to increase significantly when narrowing the defibrator's disc clearance to a particular point. In the tests in this work, 1.0 mm appears to be this point. It should be considered if it is viable to refine with smaller disc clearances. When narrowing the disc clearance, the feed rate has to be slowed down due to the longer residence time of the wood inside the refiner. Additionally, the heating up of the wood is increasing with smaller disc clearances and the wood is thus easily overheated. The lower feed rate also decreases the refining efficiency. This has an important effect on the total efficiency of the process.

The measured absolute SEC-values with the small test defibrator cannot be accurately compared to the values with modern commercial refiners, but the test results prove that there is a point where the SEC starts to increase drastically and the refining with narrower disc clearance is no more profitable.

The gathering of material inside the defibrator is a major problem, but it will probably decrease in significance in the integrated DustComb-process. There, the defibrator will be fitted with a blower, and air is blown through the defibrator. The air carries the fines from the defibrator further. However, this has not been proven in this work, and needs thus to be tested in further examination.

The particles' sizes seem not having any remarkable effect on the drying rate of the fines. However, the results are too inaccurate and no clear conclusions about the dependence between the particle size in the samples and the drying rates can thus be drawn from the drying test results. Further research is hence needed also about the drying of the fines.

6 Calculations

In this chapter, some calculations concerning the profitability of the DustComb-process are presented. First, the energy density of the DustComb-fuel is calculated and issues related to the transportation of the fuel are discussed. Then, the costs of producing the DustComb-fuel are evaluated based on the market prices of electricity and biomass. The costs are compared with the prices of coal and wood pellets, and the profitability of the DustComb-method is evaluated according to these comparisons.

6.1 Physical properties and logistics issues

As mentioned earlier in this work, the major drawbacks in biomass compared to coal are the high moisture content and low heating value. The energy density in biomass is thus also low. Table 17 presents some typical values for physical properties of different solid fuels, including the defibrated wood. The energy densities are calculated from the bulk density and the gross heating value for the specific fuel. Also, the amounts of different fuels needed to a certain power plant are presented in the table.

The fuel amounts in Table 17 are given in truck loads and the yearly energy demand of the power plant is defined as 400 GWh. It corresponds with the fuel demand of an 80 MW plant with an average usage of 5 000 hours per year. The load limit of a truck is defined as 100 m^3 and 50 tons. The densities and heating values in the table are taken from literature, except for the densities of the defibrated and slightly compressed wood, which are measured in this work. The heating values of the defibrated wood are calculated from the general heating value for wood affected by the moisture content in it.

Table 17. Physical properties of different solid fuels, including the defibrated wood with different moisture contents. The amount of truck loads is defined for a plant with a yearly fuel demand of 400 GWh. [3] [11] [13] [14]

	Coal	Peat	Wood pellets	Roundwood	Wood chips	Defibrated wood		
Moisture content mass-% (w.b.)	10	50	8	45	45	35	15	0
Bulk density								
kg/m^3	800	340	600	900	300	140	110	100
Gross heating value								
MJ/kg	25.2	9.6	16.9	8.9	8.9	11.0	15.1	18.2
kWh/kg	7.00	2.67	4.69	2.47	2.47	3.06	4.19	5.06
Energy density								
MJ/bulk-m^3	20 160	3 264	10 140	8 010	2 670	1 540	1 661	1 820
kWh/bulk-m^3	5 600	907	2 817	2 225	742	428	461	506
Truck load demand								
loads/year	1 143	4 412	1 704	3 236	5 393	9 351	8 669	7 912
loads/day	3	12	5	9	15	26	24	22

The gross heating values (GHV) for the wood fuels are estimated based on the higher heating value (HHV) and the hydrogen and moisture contents in the wood. The GHV (MJ/kg, w.b) can be calculated using the following equation:

$$Q_{GHV}\ [MJ/kg] = Q_{HHV}\left(1 - \frac{M_{wb}}{100}\right) - 2.444 \cdot \frac{M_{wb}}{100} - 2.444 \cdot \frac{X_H}{100} \cdot 8.936\left(1 - \frac{M_{wb}}{100}\right), \qquad (7)$$

where Q_{GHV} is the gross heating value [MJ/kg, w.b], Q_{HHV} is the higher heating value [MJ/kg], M_{wb} is the moisture content of the fuel on wet basis, X_H is the concentration of hydrogen (d.b) [%], 2.444 is the enthalpy difference between gaseous and liquid water at 25°C, and 8.936 is the molecular mass ratio between water (H_2O) and hydrogen (H_2). [19]

The HHV for wood in the calculations is defined as 19.5 MJ/kg and the concentration of hydrogen in the dry matter as 6.0%. Thus, the GHV-values of 8.91 MJ/kg, 11.0 MJ/kg, 15.1 MJ/kg, and 18.2 MJ/kg are resulting for the wood with moisture contents of 45%, 35%, 15%, and 0% (w.b), respectively.

The values for the energy densities and truck load demands in Table 17 are also represented in Figure 38 and Figure 39, respectively. The graphs show that the energy density of the defibrated wood is substantially lower than the energy densities of coal and wood pellets. The energy density of the defibrated wood is also clearly lower than the energy density in wood chips and roundwood, despite the lower moisture content in the refined fines. The results show that from the logistics point of view, the most cost-effective method is to transport raw roundwood to the end use plant before the defibration and drying.

It shall be noticed that the bulk density of the defibrated wood can be increased significantly by compressing it to a more compact volume. Hence, the energy density can be increased with low compression workloads. Only an enclosed storage space is needed to keep the material compact. The density of the DustComb-fuel is low because of the high amount of air between the particles. So, to densify the fuel it is also possible to remove the air with vacuum pumps. Further research regarding the compaction of the material is though still needed.

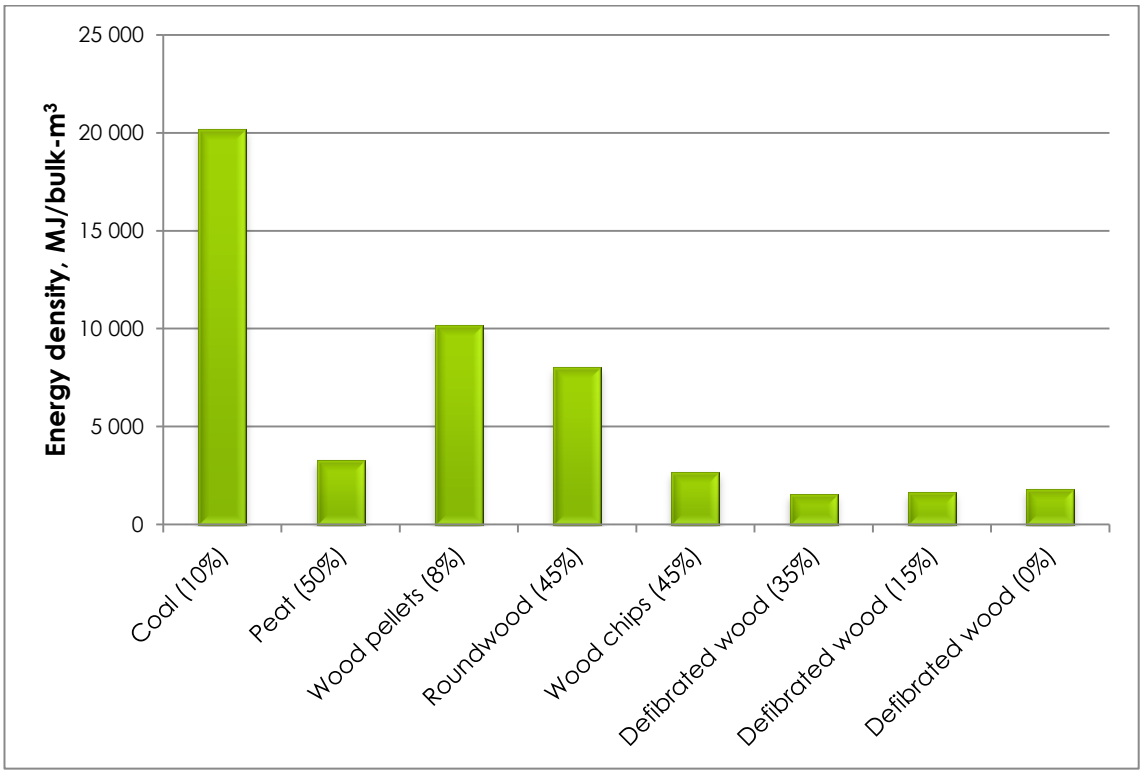

Figure 38. Bulk energy densities for different solid fuels. The moisture contents of the fuels on wet basis are presented in the parentheses.

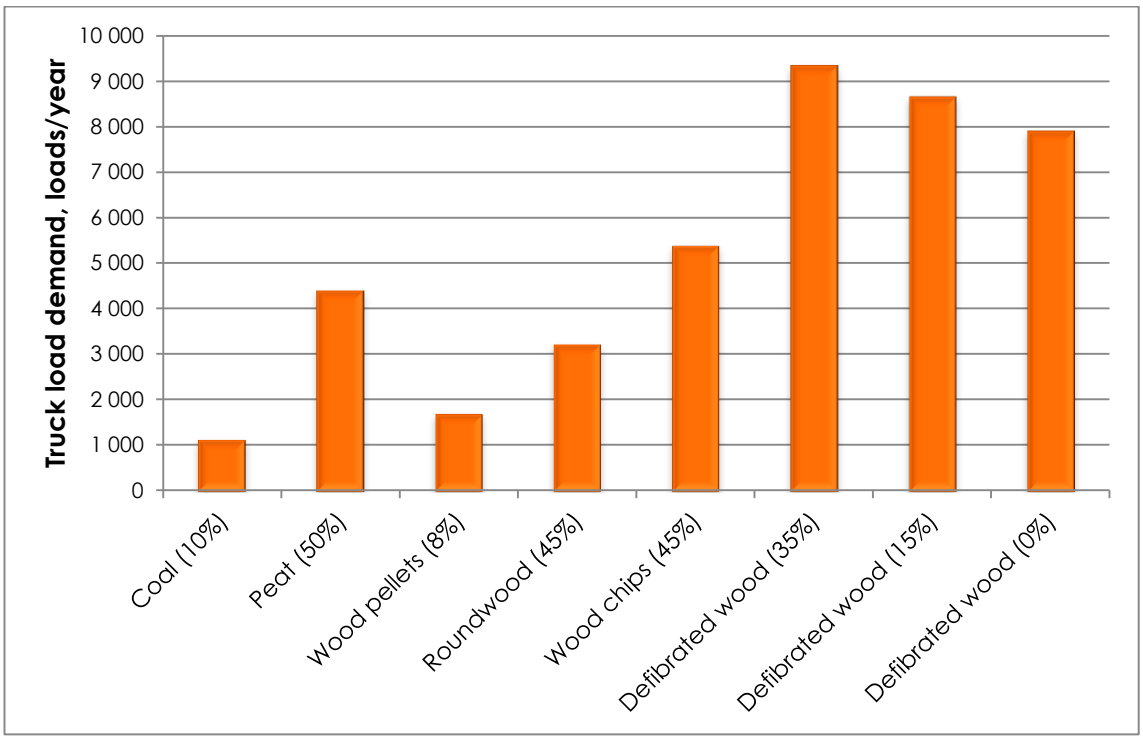

Figure 39. Estimated amount of truck loads needed for different fuels to a plant with a yearly fuel demand of 400 GWh. The load limit of a truck is defined as 100 m^3 and 50 tonnes. The moisture contents of the fuels on wet basis are presented in the parentheses.

6.2 Cost analysis

In this chapter, the production costs of the DustComb-fuel are evaluated and compared with the prices of coal and wood pellets. The costs are calculated based on the market prices of the feedstock and electricity. In all cases, the fuels are assumed to be combusted in a CHP-plant. Furthermore, sensitivity analyses are performed to examine how the production costs are affected by varying parameters, such as electricity price, heat price and biomass price.

6.2.1 Fuel prices

The market fuel prices, taxes and fees used in the calculations in this work are presented in Table 18.

Table 18. Fuel and electricity market prices and taxes in Finland in spring 2013. The prices are presented per ton of fuel and per MWh of energy in the fuel. [46] [47] [48] [49]

	€/t	€/MWh
Coal		
Market price (average)	70.00	10.00
Energy content tax	47.10	6.73
Carbon dioxide tax	84.43	12.06
Strategic stockpile fee	1.18	0.17
CO_2-emission allowance	4.00 (€/t_{CO2})	1.36
Wood pellets	-	30.63
Forest Biomass	-	19.12
Electricity	N/A	44.00

In Finland, the taxation of coal depends on the coal's purpose of use. No taxes or strategic stockpile fees are paid for coal used for electricity production, unlike the coal used for heat generation. In combined heat and power generation, coal taxes are paid only for the share of heat in the total energy output. In other words, the fuel power which is calculated to be converted into electricity is not taxed.

The amount of burned coal for the heat share in a CHP-plant is calculated from the amount of distributed useful heat. This amount is further multiplied with the coefficient 0.9. In addition, the carbon dioxide tax for the coal in CHP-plants is only the half of the value in Table 18, i.e. 6.03 €/MWh. The amount of CO_2-emissions from coal is calculated by multiplying the energy content in coal by the factor 0.34 t_{CO2}/MWh. [50]

So, the total specific coal prices for the generated electricity and heat in a CHP-plant are counted separately using Equations (8) and (9). Also the total fuel price in the combined heat and power production are calculated using Equation (10). The share of heat is assumed to be 65% of the total output (power and heat). The same proportions for output heat and power are assumed to apply also on the input fuel power.

$$C_{Fuel,el} = 10.00\,\frac{€}{MWh} + 1.36\,\frac{€}{MWh} = 11.36\,\frac{€}{MWh} \quad (8)$$

$$C_{Fuel,CHP-heat} = 10.00\,\frac{€}{MWh} + 0.9 \cdot (6.73 + 6.03 + 0.17)\,\frac{€}{MWh} + 1.36\,\frac{€}{MWh} = 23.00\,\frac{€}{MWh} \quad (9)$$

$$C_{Fuel,comb} = 0.35 \cdot 11.36\,\frac{€}{MWh} + 0.65 \cdot 23.00\,\frac{€}{MWh} = 18.93\,\frac{€}{MWh}, \quad (10)$$

where $C_{Fuel,\ el}$ is the fuel costs for the generated electricity, $C_{Fuel,\ CHP\text{-}heat}$ is the fuel costs for the generated heat in a CHP-plant, and $C_{Fuel,\ comb}$ is the total fuel costs for the combined generation.

The price of the coal burned in a condensate power plant for electricity production is the same as the coal costs for generated electricity in a CHP-plant, i.e. 11.36 €/MWh. If the coal is burned in a plant where only heat is produced, the amount of taxes and fees are the full amounts given in Table 18. The total fuel price in this case is:

$$C_{Fuel,heat} = (10.00 + 6.73 + 12.06 + 0.17 + 1.36)\,\frac{€}{MWh} = 30.32\,\frac{€}{MWh}\,, \quad (11)$$

where $C_{Fuel,\ heat}$ is the fuel costs for the generated heat.

No additional taxes or costs are paid for renewable fuels, such as wood pellets or forest biomass. The renewable fuels are also exempted from the CO_2-emission allowance costs.

The true value of the district heat generated in a CHP-plant can be hard to define because of the separately defined market price of electricity. One method to calculate the value of heat is the first residual method, where the price of heat is the remaining value of the fuel when the value of electricity produced in the plant is subtracted from the price of the fuel. This is clarified in Equation (12). [51]

$$C_{CHP-heat} = \frac{(1+\alpha) \cdot C_{fuel}}{\eta} - \alpha \cdot C_{el}\,, \quad (12)$$

where $C_{CHP\text{-}heat}$ is the price of heat [€/MWh], α is the power to heat ratio, C_{Fuel} is the price of coal [€/MWh], η is the plant efficiency, and C_{el} is the market price of electricity [€/MWh].

The power to heat ratio is calculated by dividing the generated amount of power with the amount of heat. For a plant where the share of heat in the total output is 65%, the power to heat ratio is 0.54. The efficiency in a CHP-plant is assumed to be 85%. By using the electricity market price of 44 €/MWh and the total coal price in CHP-production of 18.93 €/MWh from Equation (10), the resulting price of the heat is:

$$C_{CHP-heat} = \frac{(1+0.54) \cdot 18.93\ €/MWh}{0.85} - 0.54 \cdot 44.00\,\frac{€}{Mwh} = 10.53\,\frac{€}{MWh} \quad (13)$$

The fluctuations in the electricity market price can be remarkable compared to the more stable market price of coal. [46] When the electricity price is high, the price of district

heat in a CHP-plant may decrease to negative. In such cases, the plant may usually still be run, but as a condensate plant to generate higher amounts of electricity. The relation between the market price of electricity and residual price of heat are presented in Figure 40. It can be seen that with current coal prices, the price of heat becomes negative when the electricity price exceeds 64 €/MWh.

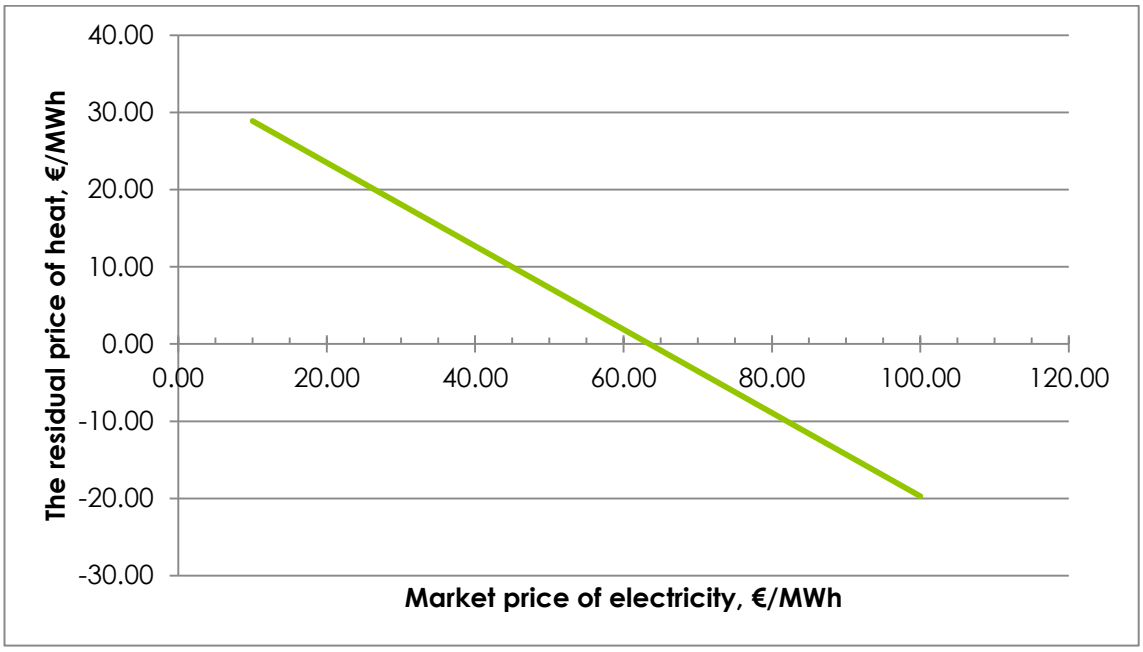

Figure 40. The dependence of the electricity market price on the value of the generated heat. The value of heat is calculated with the first residual method (Equation 12) with the fuel price of 18.93 €/MWh.

6.2.2 Production costs of the DustComb-fuel

In the following calculations, the production costs of the DustComb-fuel are estimated. The costs include the price of the feedstock and the costs of consumed power and heat for the defibration and drying. The production costs are evaluated for two DustComb-cases:

1. In the first case, the SEC for defibration is assumed as the optimal based on the tests in Chapter 5, i.e. 600 kWh/t, and the SEC for drying is assumed as a feasible consumption level in modern flash dryers according to literature. The typical energy consumption range (4 500 to 9 000 kJ/kg) in flash dryers is presented in Chapter 4.3.2.
2. In the second case, the costs are evaluated with a significantly lower, but still realistic defibration SEC. Such low SEC-level is assumed to be reached by using modern large-scale defibrators. The dryer's SEC is defined as the same as in the first case.

The both cases are further divided into three subcases depending on the price of the heat consumed in drying. As mentioned earlier, the price of process heat can be difficult to define, because it depends on the source where it is generated. Several methods exist to calculate the value of heat, of which one was presented in Equation (12). The heat prices in the calculations are the following:

A. Low price: 2 €/MWh. Equivalent to the price of excess heat, where only eventual pumping and investment costs are included.
B. Medium price: 10 €/MWh. Equivalent to the price of district heat calculated in Equation (13).
C. High price: 30 €/MWh. Equivalent to the costs of heat generated for example from coal in a heat boiler (Equation 11).

The parameters for each case and subcase are summarized in Table 19.

Table 19. The calculation parameters for the different cases.

		Case 1 Experimental defibration SEC			Case 2 Assumed defibration SEC		
Parameter		A	B	C	A	B	C
Heat price	€/MWh	2	10	30	2	10	30
Electricity price	€/MWh	44	44	44	44	44	44
Refining SEC	kWh/t_{dry}	600	600	600	100	100	100
Drying SEC	kJ/kg_{H2O}	4 500	4 500	4 500	4 500	4 500	4 500

The flow chart of the DustComb-process with the calculation values in Case 1 (mass and energy flows, moisture contents, heating values, and prices) is presented in Figure 41. The mass and energy flows in the chart are presented per kg of input moist chips. The amount of removed water is calculated from the measured changes in the moisture contents during defibration and drying. The specific amounts of consumed electricity and heat are calculated based on the SEC-values for the defibration and drying.

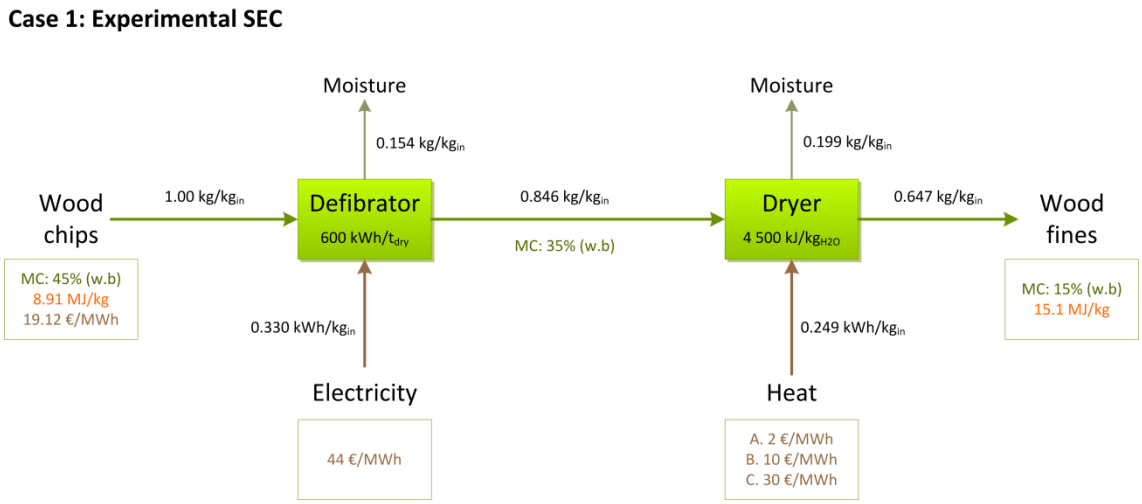

Figure 41. Flow chart of Case 1. The values in the chart represent mass and energy flows per kg of fed moist chips (black), moisture contents (green), heating values (orange), and prices (brown).

The production cost calculations in Case 1A are presented in the following equations. The values for the calculations are taken from Figure 41.

First, the price of wood chips is converted into €/ton:

$$\left(8\,910\,\frac{MJ}{t}/3\,600\,\frac{MJ}{MWh}\right)\cdot 19.12\,\frac{€}{MWh}=47.322\,\frac{€}{t_{in}} \quad (14)$$

The processing costs, i.e. the price of consumed electricity and heat per input ton of chips, are then calculated by multiplying the consumed amount with its price:

$$0.330\,\frac{MWh}{t}\cdot 44\,\frac{€}{MWh}+0.249\,\frac{MWh}{t}\cdot 2\,\frac{€}{MWh}=15.018\,\frac{€}{t_{in}} \quad (15)$$

The total costs per input ton of chips are received by adding the price of consumed energy to the price of wood chips. The total costs per input ton are divided by the yield rate and output heating value to receive the costs per yielded MWh of fuel:

$$(47.322+15.018)\,\frac{€}{t_{in}}/\left(0.647\,\frac{t}{t_{in}}\cdot\frac{15\,110\,MJ/t}{3\,600\,MJ/MWh}\right)=22.96\,\frac{€}{MWh} \quad (16)$$

The costs are calculated similarly for the different heat prices in the both cases. The flow chart and the calculation values for Case 2 are presented in Figure 42. The results from both DustComb-cases are compared with the market prices of coal and wood pellets and presented in Figure 43. The amount of taxes and additional costs for the coal are added according to the combustion of coal in a CHP-plant with power-to-heat ratio of 0.54. This is calculated in Equation (10) with total coal price resulting in 18.93 €/MWh.

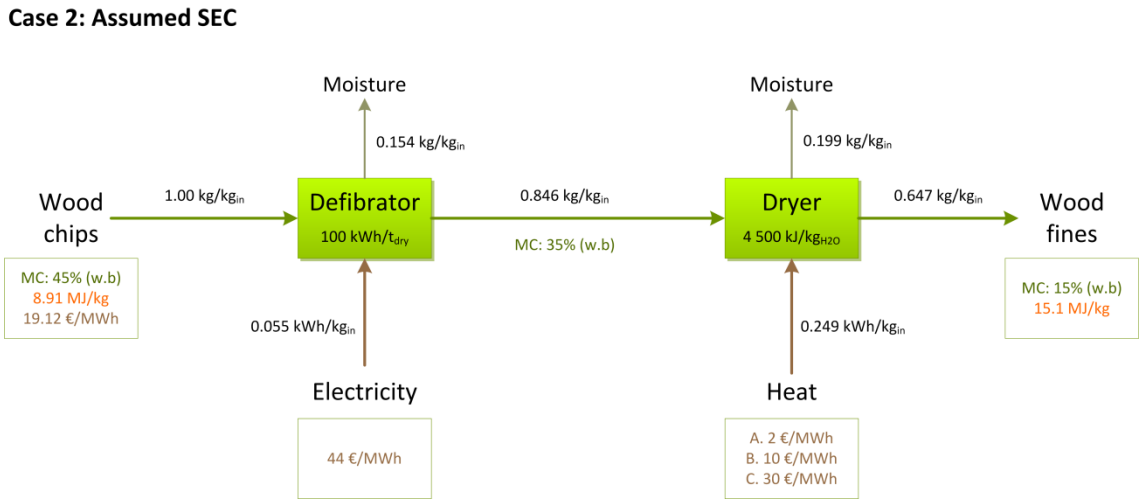

Figure 42. Flow chart of Case 2. The values in the chart represent mass and energy flows per kg of fed moist chips (black), moisture contents (green), heating values (orange), and prices (brown).

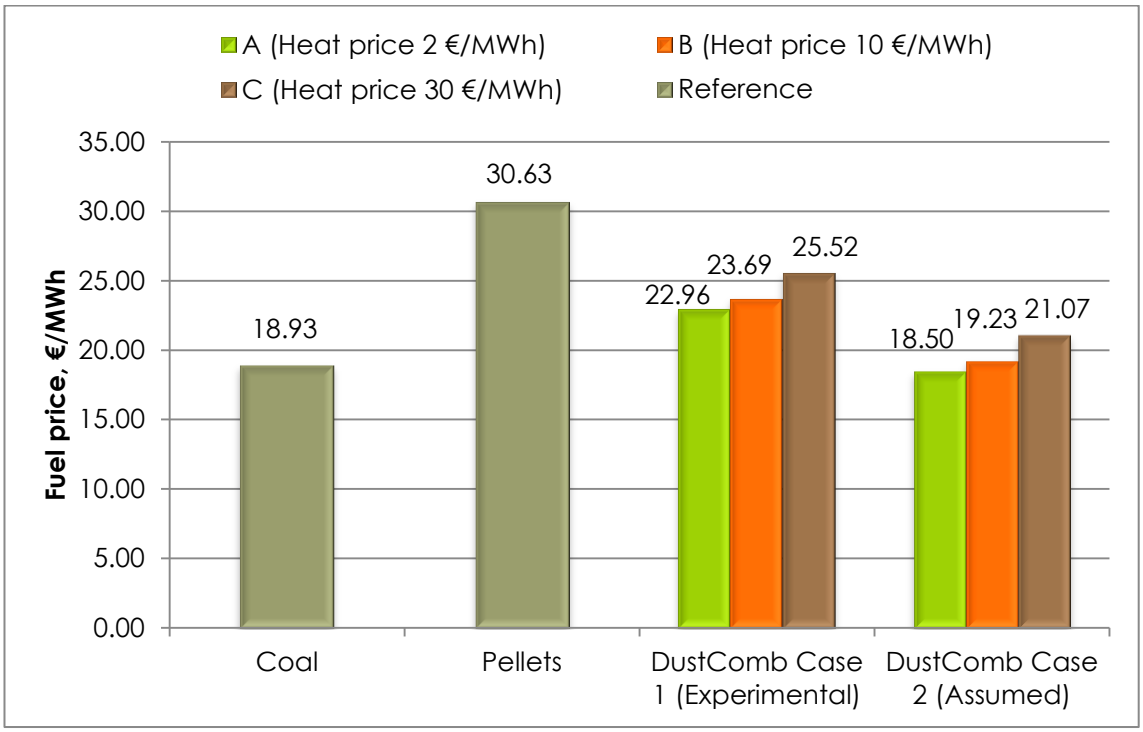

Figure 43. The total costs of the DustComb-fuel in the both cases and with different heat prices. The fuel prices of coal and wood pellets are given as reference prices.

Figure 43 shows that it is possible to produce DustComb-fuel with competitive expenses. The costs of the most profitable cases, i.e. Cases 2A and 2B, are at the same level as the price of coal. It is also noticeable that the costs in all cases are remarkably lower than the current market price of wood pellets. In condensate plants, where the price of coal is lower (11.36 €/MWh, Equation 8), the replacing of coal with the DustComb-fuel would not be lucrative.

Additional power consumption (pumps, fans, refiner's idling power, etc.) is not taken into account in the DustComb cases. This will increase the fuel price slightly. However, the pretreatment costs of coal and pellets before combustion, such as electricity consumption of mills and blowers, are not either included in their prices. The coal and pellet prices will thus also increase if these costs are added.

6.2.3 Sensitivity analyses

In this chapter, sensitivity analyses are performed for the DustComb-fuel's production costs based on the market prices of electricity, heat and raw material. Also, the effects of varying CO_2-allowance price and share of biomass in co-firing are evaluated. The DustComb-cases with the highest and lowest expenses according to Figure 43, i.e. cases 1C and 2A, respectively, are used and compared with coal and pellet prices.

Electricity price

As mentioned previously in this work, the market price of electricity tends to fluctuate strongly. Hence, a sensitivity analysis over the DustComb's costs is done for varying market price of electricity. The results are presented in Figure 44. The fuel pretreatment

costs for wood pellets and coal are not taken into account in the calculations. Thus, the fuel price of coal and pellets are constant in the figure.

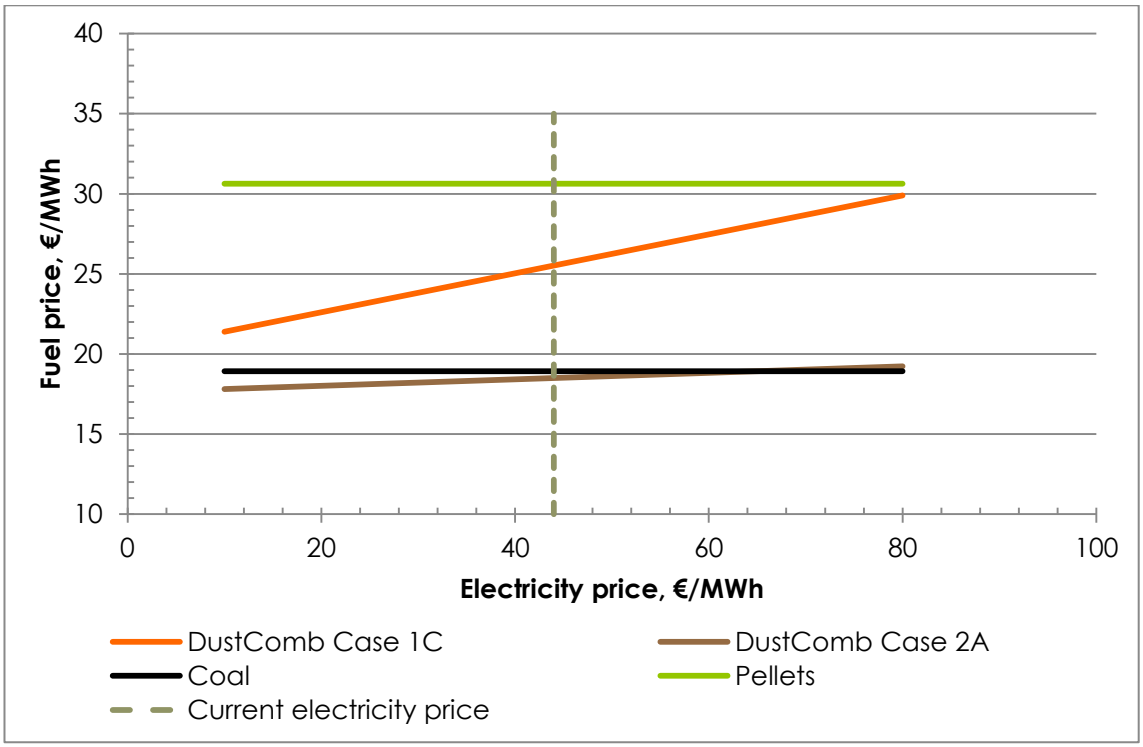

Figure 44. Dependence of the electricity market price on the fuel prices.

Figure 44 shows a great difference in the fuel prices between the low- and the high-priced DustComb cases. The price of the DustComb-fuel in Case 1C is significantly more dependent on the electricity price than in Case 2A. This is explained by the six times higher power consumption in Case 1. If the DustComb-fuel was produced with equivalent SEC-values as in Case 2, the DustComb would be very competitive with the coal price in a CHP-plant even if the electricity market price is increased to almost the double from the current price. Figure 44 shows also that the DustComb-fuel is in all cases still more cost-effective than wood pellets.

Heat price

The costs for different heat prices are calculated in the three subcases and presented in Figure 43. The effect of increasing heat price is though further presented in Figure 45 for the both DustComb-cases. With current fuel prices, the heat can be assumed as very expensive if it increases above 30 €/MWh. For example, if the heat price is calculated using the first residual method (Equation 12, Figure 40), the market price of electricity has to be exceptionally low to cause the price of heat to increase above 30 €/MWh.

However, even with heat prices over 60 €/MWh, the price of DustComb-fuel is lower than the price of pellets. The DustComb is though more expensive than coal, except for Case 2 with heat prices lower than 8 €/MWh.

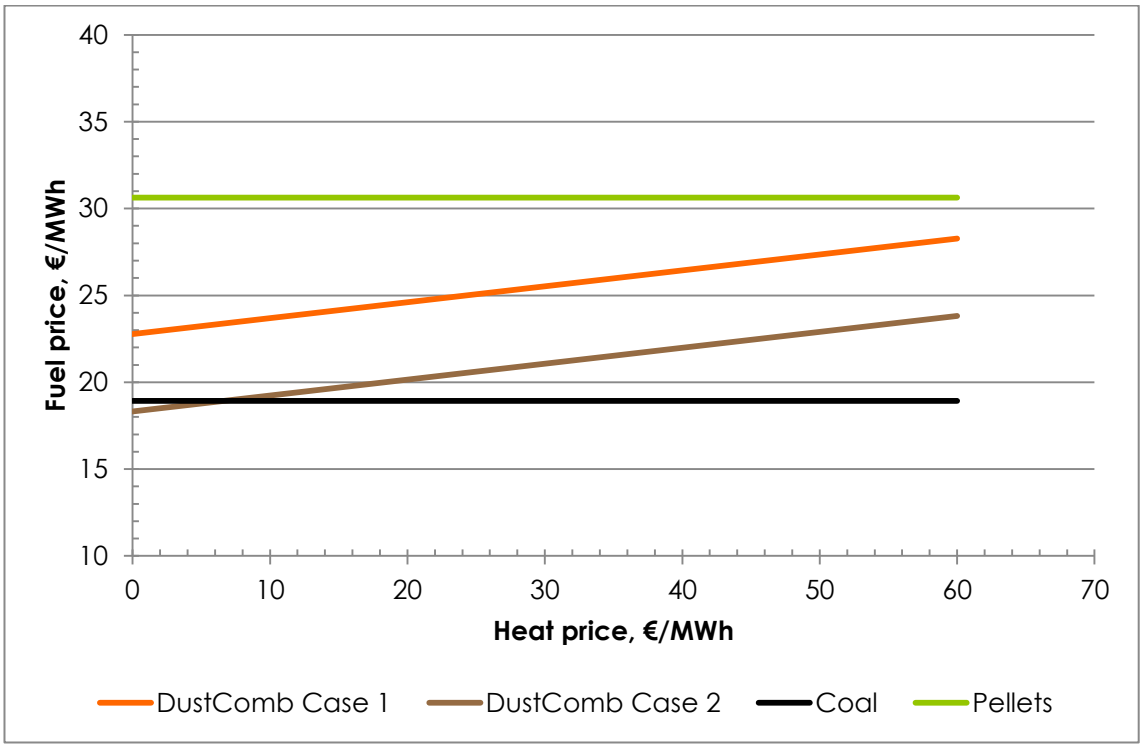

Figure 45. Dependence between the value of the drying heat and the fuel production costs.

Biomass price

The market price of forest biomass has increased from 13 €/MWh to over 19 €/MWh since 2007. [46] Further increase may have a significant effect on the profitability of the DustComb-fuel. So, also the effect of the feedstock price on the price of the DustComb-fuel is evaluated. The analysis results are presented in Figure 46.

Figure 46 shows a drastic increase in the production costs of the DustComb-fuel when the biomass price increases. Even a low increase in the biomass price may cause the costs of producing the DustComb-fuel to increase above the price of wood pellets. On the other hand, if low-priced biomass is available, even fuel produced with the most expensive DustComb-case can be more economical than coal. It shall be noticed that all fuel prices are generally speaking increasing in time. [46] So if the fuel prices are compared with each other in the long run, also the prices of pellets and coal have to be revised.

When comparing Figures 44, 45 and 46, it can be noticed that the price of the feedstock has the highest impact on the total fuel production costs. In other words, the processing costs of the wood have a small influence on the total production costs of the DustComb-fuel compared to the price of the feedstock.

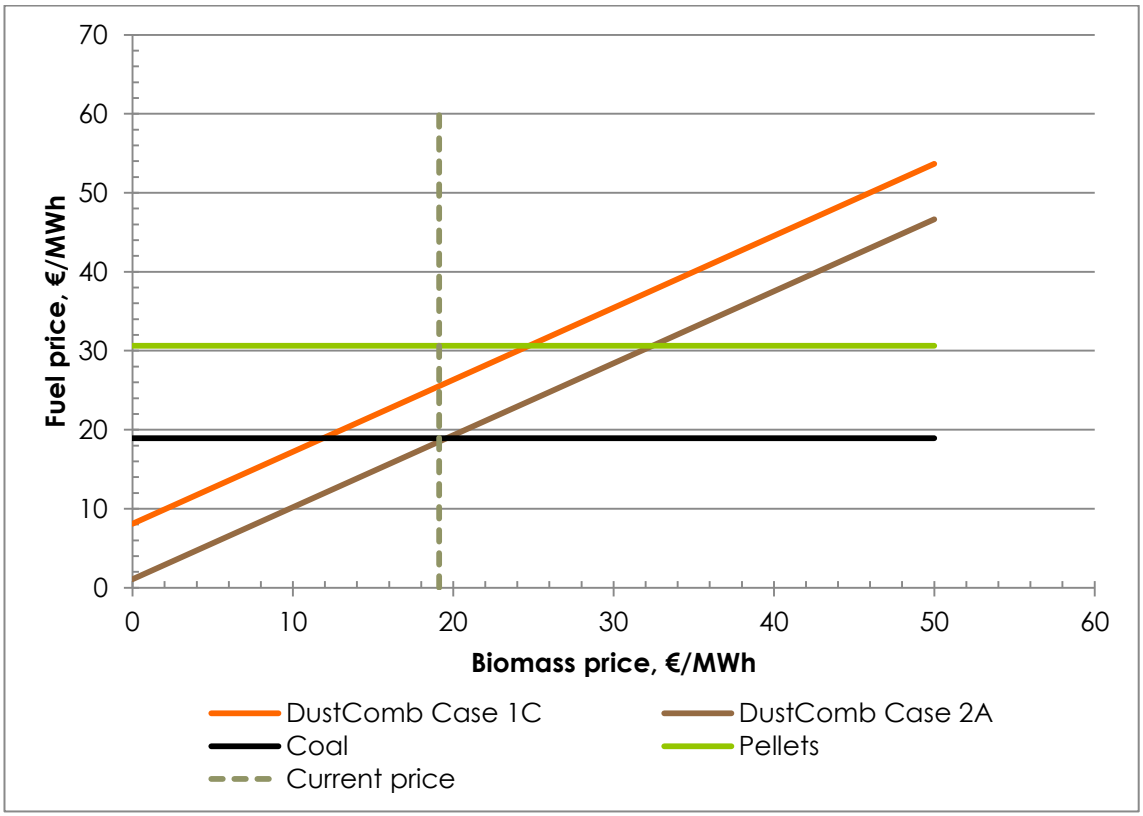

Figure 46. Dependence between the price of biomass and the production costs of the DustComb-fuel.

CO_2-emission allowance price

The CO_2-emissions are striven to be controlled by emission allowances in the EU. The price of emission allowances has fluctuated strongly, and since 2008 the price has decreased from more than 25 €/t to the current price of below 4 €/t. [7] [48] The energy generation costs in the different cases are thus calculated and compared for changing CO_2-allowance prices.

Because the price of electricity generated in a power plant is defined by the market price, it is not affected by the generation costs. So, to compare how the CO_2-allowance price affects the costs of energy generation in a CHP-plant, the costs are calculated for the generated district heat. The heat price is calculated with the first residual method (Equation 12) and the results are presented in Figure 47.

The fuel costs are calculated for co-firing of biomass with coal. The share of biomass in the total fuel power is 20% in the DustComb- and pellet-cases. The rest 80% of the fuel power is defined to originate from coal. In the coal-case, only coal is combusted.

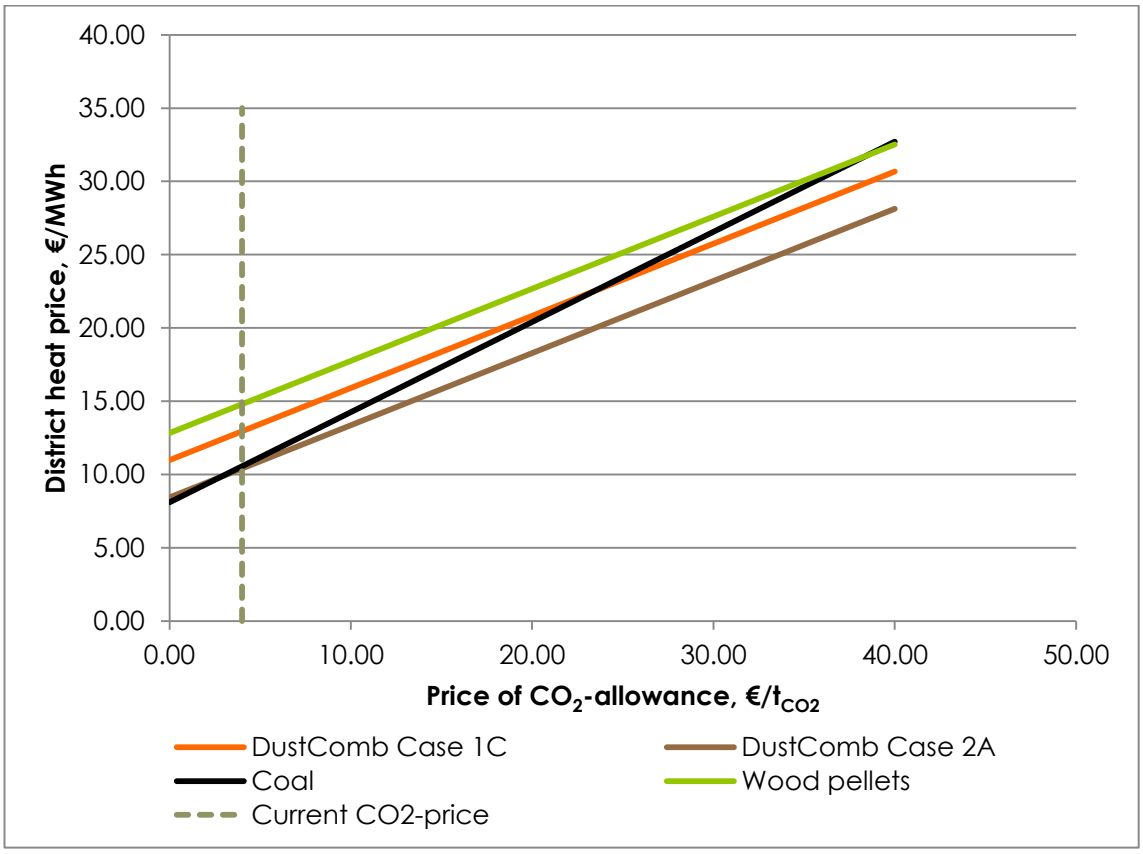

Figure 47. Dependence between the price of district heat and the CO_2-allowance price. The heat is generated in a CHP-plant and its price is calculated with Equation (12). In the DustComb- and pellet-cases, the biofuel is co-fired with coal with a share of 20% of total fuel power.

Because all cases include combustion of coal, all prices are increasing when the CO_2-allowance price is increased. The amount of burned coal in the coal-case is however higher than in the other cases and its costs increase thus steeper with increasing allowance price. The profitability of the DustComb-fuel compared to coal increases with increasing CO_2-price.

Share of biomass

In co-firing, the share of biomass affects the price of generated energy because of the different prices between coal and biofuels. The dependence between the biomass share in the fuel and the district heat price is calculated and presented in Figure 48. The pellet-fuel, which is the most expensive fuel in this comparison, causes the highest increase in the energy price when its share in co-firing is increased. The energy generation costs with the most cost effective DustComb-case, on the other hand, decrease slightly as the biomass share increases. So, from a consumer's point of view, the price of district heat may not be affected if DustComb-fuel is combusted together with coal.

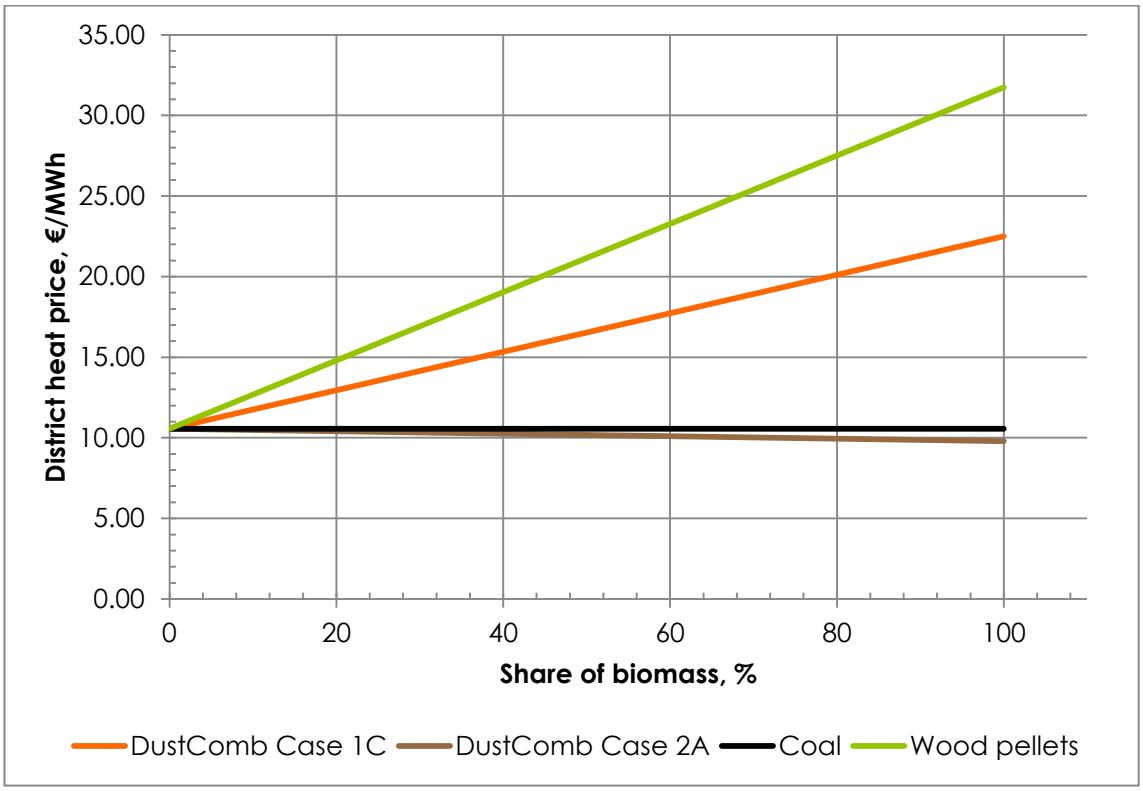

Figure 48. Dependence between the price of district heat and the biomass share in co-firing with coal. The heat is generated in a CHP-plant and its price is calculated with Equation (12).

6.3 CO_2-savings

The CO_2-emissions from fossil coal are reduced when the coal is replaced with biofuels. The total amounts of CO_2 emitted from the production of the DustComb-fuel and co-firing are estimated in this chapter. The estimated amounts are calculated for the both DustComb-cases, which were presented in Chapter 6.2.2, and they are calculated in two steps:

1. The emissions are calculated for the share of coal in the co-firing and for the electricity generation required for the defibration. The electricity is defined to be generated in a coal-fired condensate plant. The emissions from the generation of the drying heat are ignored.
2. The total emissions are then calculated by adding the emissions from heat generation to the total emissions in the first calculation. The heat is generated by burning methane with 100% efficiency.

The total emissions are calculated per MWh of generated live steam in the boiler. The emissions are calculated for the Case 1 in the following equations, and the values in Figure 41 are used as calculation parameters.

The live steam is assumed to be generated with 85% boiler efficiency. Thus, the amount of formed CO_2 when burning 100% coal is calculated by dividing the CO_2 formation factor from coal with the efficiency.

$$0.34 \frac{t_{CO2}}{MWh_{coal}} / 0.85 = 0.40 \frac{t_{CO2}}{MWh_{steam}} \quad (17)$$

When 20% of the coal is replaced by the DustComb-fuel, the specific biofuel power is:

$$0.20\,\frac{MWh_{bio}}{MWh_{in}}/0.85 = 0.2353\,\frac{MWh_{bio}}{MWh_{steam}} \quad (18)$$

The fuel power is divided by the heating value of the fuel to receive the specific biofuel consumption:

$$235.3\,\frac{kWh_{bio}}{MWh_{steam}}\Big/\frac{15.11\ MJ/kg}{3.600\ MJ/kWh} = 56.06\,\frac{kg_{bio}}{MWh_{steam}} \quad (19)$$

The specific feed of wood chips into the DustComb-process per generated MWh of live steam is calculated by dividing the fuel consumption from Equation (19) with the DustComb yield rate:

$$56.06\,\frac{kg}{MWh_{steam}}/0.647\,\frac{kg}{kg_{chips}} = 86.65\,\frac{kg_{chips}}{MWh_{steam}} \quad (20)$$

The amounts of electricity and heat needed for the DustComb-process per MWh of generated live steam are calculated using the Equation (21) and (22), respectively.

$$0.330\,\frac{kWh_{el}}{kg_{chips}} \cdot 86.65\,\frac{kg_{chips}}{MWh_{steam}} = 28.59\,\frac{kWh_{el}}{MWh_{steam}} \quad (21)$$

$$0.249\,\frac{kWh_{heat}}{kg_{chips}} \cdot 86.65\,\frac{kg_{chips}}{MWh_{steam}} = 21.58\,\frac{kWh_{heat}}{MWh_{steam}} \quad (22)$$

The CO_2-emissions formed when generating the required electricity with a condensate coal-fired plant with total efficiency of 40% is calculated using Equation (23):

$$\left(0.02859\,\frac{MWh_{el}}{MWh_{steam}}/0.40\,\frac{MWh_{el}}{MWh_{coal}}\right) \cdot 0.34\,\frac{t_{CO2}}{MWh_{coal}} = 0.0243\,\frac{t_{CO2}}{MWh_{steam}} \quad (23)$$

The CO_2-emissions formed when generating the required amount of heat by direct combustion of methane is calculated using Equation (24). The efficiency is assumed as 100%, and the specific CO_2 formation factor of methane is 0.20 t_{CO2}/MWh_{CH4}.

$$\left(0.02158\,\frac{MWh_{heat}}{MWh_{steam}}/1.00\,\frac{MWh_{heat}}{MWh_{CH4}}\right) \cdot 0.20\,\frac{t_{CO2}}{MWh_{CH4}} = 0.00432\,\frac{t_{CO2}}{MWh_{steam}} \quad (24)$$

First, when the emissions from the heat generation are ignored, the total net CO_2-emissions are calculated by adding the emissions from the share of coal in co-firing with the emissions from the electricity generation. If the share of DustComb-fuel in co-firing is 20%, the result from Equation (23) is added to the emissions from the rest 80% coal. So, the total CO_2-emissions are:

$$0.80 \cdot 0.40\,\frac{t_{CO2}}{MWh_{steam}} + 0.0243\,\frac{t_{CO2}}{MWh_{steam}} = 0.344\ \frac{t_{CO2}}{MWh_{steam}} \quad (25)$$

The net emissions are calculated similarly for the both cases and for different DustComb-fuel shares in the co-firing. The results are presented in Figure 49. The total CO_2-emissions, including the emissions from the heat generation, are presented in Figure 50.

Figure 49 and Figure 50 show that even though the energy required for the DustComb-process is generated with fossil fuels, the net CO_2-savings with the DustComb are significant. If this energy was moreover assumed to be generated from renewable sources, the total emissions would reduce further.

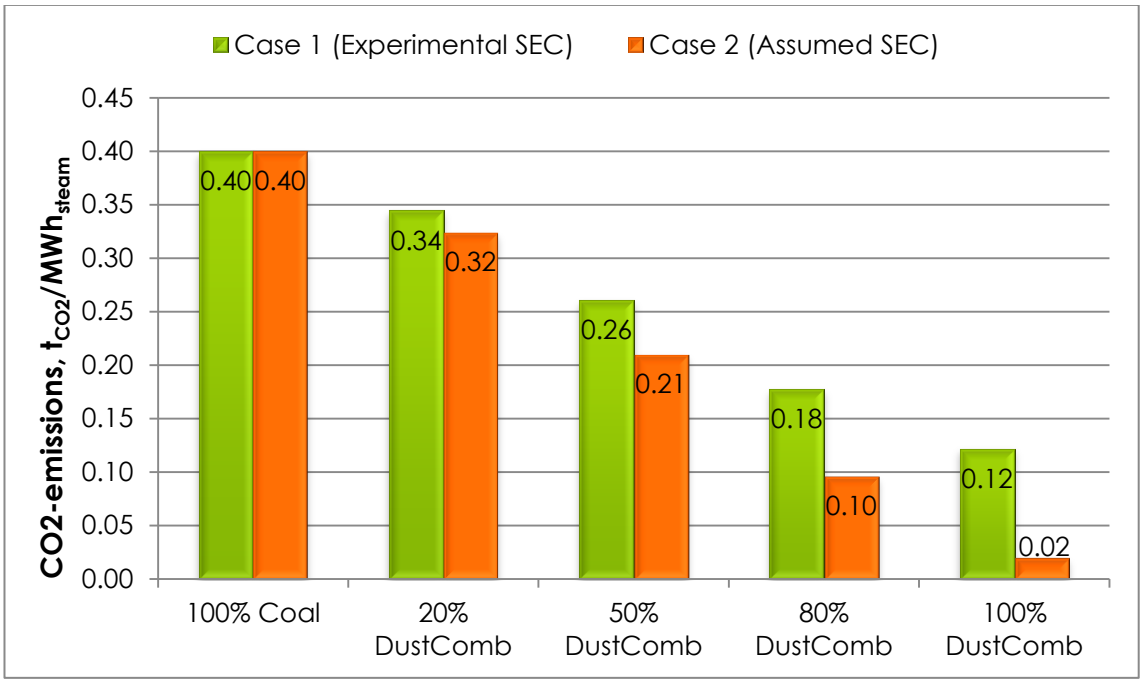

Figure 49. Total CO_2-emissions per generated MWh of live steam with different DustComb-fuel shares. The amounts include the emissions from the share of coal, and the emissions from electricity generation for the DustComb-process. The emissions from heat generation for the drying are not included.

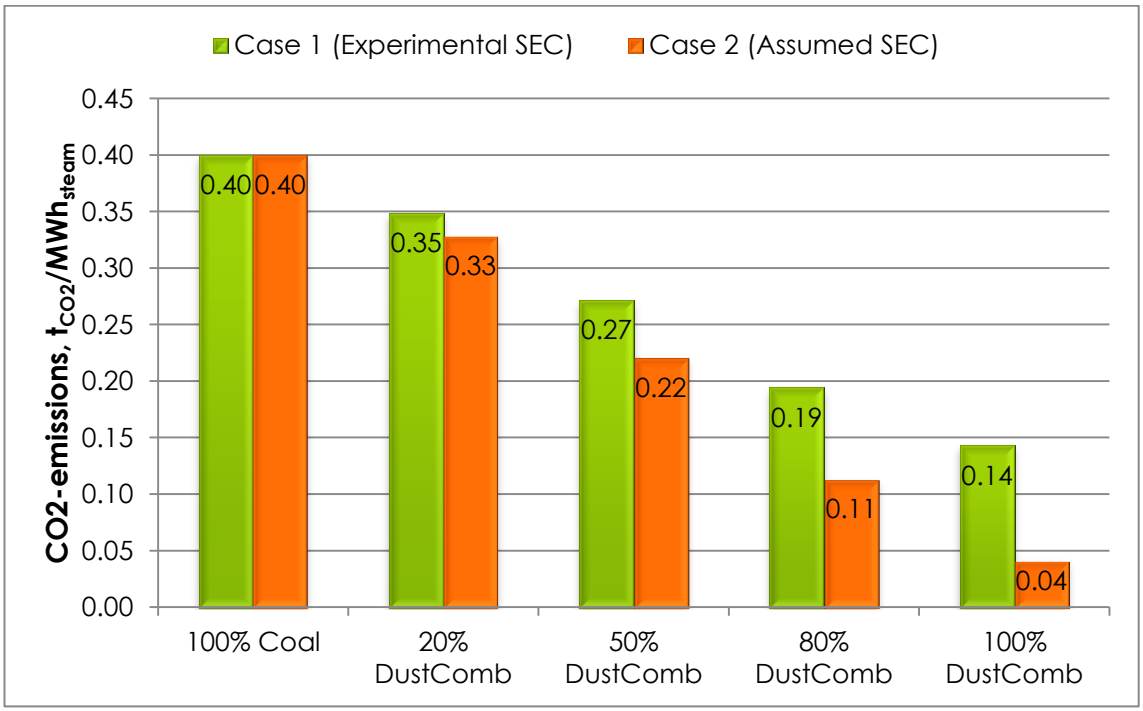

Figure 50. Total CO_2-emissions per generated MWh of live steam with different DustComb-fuel shares. The amounts include the emissions from the share of coal, and the emissions from electricity and heat generation for the DustComb-process.

7 Conclusions

According to the test results in this work, the DustComb-process seems to be a suitable method for producing wood fines for pulverized fuel firing. The wood can be defibrated with relatively low power consumption, if the clearance between the refining discs is kept wide enough. In this study, the energy consumption of the defibration started to increase drastically when the disc clearance was narrowed from 1.0 mm. If no water is fed with the wood chips into the defibrator, the wood dries remarkably during the defibration. This reduces the amount of heat required in the dryer. 16-25% of the moisture in the wood chips was removed during the defibration tests in this work.

With current market prices of coal and biomass, the DustComb-fuel can be produced with competitive costs compared to the price of coal in a CHP-plant. The production costs depend on the prices of electricity, heat and raw material, and the specific energy consumptions in the defibration and drying. The processing costs, i.e. the costs of consumed energy in the DustComb-process, are however relatively low compared to the price of the feedstock. Even a low decrease in the biomass market price can increase the profitability of the DustComb significantly compared to the use of coal.

Even though the energy required for the DustComb-process was generated from fossil sources, the net fossil CO_2-emissions are reduced when the share of DustComb-fuel in co-firing is increased. The emissions from the transportation of the fuels are not taken into account in this work. So, to estimate the total CO_2-emissions, the transportation issues of the DustComb-fuel have to be further analyzed. Also the compacting of the fuel needs to be studied to find out the most efficient way to store and transport the fuel.

The results of this study show that application of the DustComb-method in pulverized fuel firing is feasible, but further research is still required on the following topics:

- The behavior of the defibrated fines in a flash dryer and in pulverized fuel burners.
- The influence of different particle sizes and moisture contents on the combustion quality.
- The drying rate of the fines between the defibrator and the dryer, and the real need of heat in the dryer.
- The total costs of the DustComb-process when the energy consumption of the blowers and pumps are included.
- A complete life-cycle assessment on the fuel production, including the transportation costs, etc.
- The influence of the wood fines on the combustion when co-fired together with coal (eventual influence on e.g. the boiler efficiency, emissions and acid dew point).

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